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Unattended Network Operations Technology Assessment Study

Kent M. Price

Space Systems/Loral, Palo Alto, California 94303-4606

Mark Holdridge, Jide Odubiyi, Allan Jaworski, and Herbert K. Morgan

Loral AeroSys, Seabrook, Maryland 20706-2257

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Technical Support for Defining
Advanced Satellite Systems Concepts

Final Report for Task Order 3:
**UNATTENDED NETWORK OPERATIONS
TECHNOLOGY ASSESSMENT STUDY**

Managed by:
Space Systems/Loral, 3825 Fabian Way
Palo Alto CA 94303-4606

Technical Support by:
Loral AeroSys, 7375 Executive Place
Seabrook, MD 20706-2257

Program Manager: Kent M. Price, Space Systems/Loral

Major Contributors: Mark Holdridge, Loral AeroSys
Jide Odubiyi, PhD, Loral AeroSys
Allan Jaworski, PhD, Loral AeroSys
Herbert K. Morgan, Loral AeroSys

Prepared for
NASA, Lewis Research Center
Cleveland, OH 44135

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List of Acronyms

ABE	An Environment for Building Intelligent Systems
ACTS	Advanced Communications Technology Satellite (of NASA)
AF	Activation Framework
AI	Artificial Intelligence
ANS	Artificial Neural System
CCD	Charge-Coupled Device
CMIP	Common Management Information Protocol
CMOT	Common Management Protocol Over TCP/IP
DAI	Distributed Artificial Intelligence
DBMS	Data Base Management System
DoD	Department of Defense
DPS	Distributed Problem Solving
DSN	Deep Space Network (of NASA)
EMA	Enterprise Management Architecture
ERS	Earth Relay Satellite
EST	Earth Surface Terminal
FDDI	Fiber Distributed Data Interface
FDMA	Frequency Division Multiple Access
HIPPI	High Performance Parallel Interface
INM	Integrated Network Management
ISDN	Integrated Services Digital Network
ISO	International Standards Organization
LAN	Local Area Network
LOS	Line Of Sight
LRS	Lunar Relay Satellite
MACE	Multi-Agent Computing Environment
MCH	Mars Communications Hub
MEV	Mars Excursion Vehicle
MMIC	Monolithic Microwave Integrated Circuit
MPRS	Mars Polar Orbiting Relay Satellite
MRS	Mars Relay Satellite
MST	Mars Surface Terminal
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
MTV	Mars Transfer Vehicle
NASCOM	NASA Communications Network
OSI	Open System Interconnect
SCPC	Single Channel Per Carrier
SEI	Space Exploration Initiative
SNMP	Simple Network Management Protocol
TDMA	Time Division Multiple Access
TDRS	Tracking and Data Relay Satellite
TNIM	Telecommunications, Navigation, and Information Management
TWTA	Traveling Wave Tube Amplifier
UNMA	Unified Network Management Architecture
WAN	Wide Area Network

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Summary

The Telecommunications, Navigation, and Information Management (TNIM) system will be a major element in the Space Exploration Initiative (SEI). Certain time-critical TNIM functions will have to be handled at Mars to avoid the 8 to 40 minute Earth reaction time due to the round trip transmission delay. With a limited number of astronauts at Mars, it will be imperative that those time-critical functions executed at Mars require little or no input from the astronauts.

TNIM functions during the Apollo era did not suffer from Earth-centered control delays because the round trip time was only a matter of seconds between the Earth and Moon. NASA communications networks during the Apollo era and up to the present time have been very manpower intensive and therefore have not run unattended. Hence the need exists to develop unattended network elements to support SEI communications. The alternative would be an awkward, non-responsive TNIM system for Mars exploration which could jeopardize the health and safety of the Mars astronauts.

The purpose of this study was to explore how a Mars-centered communications network could be designed to run in a virtually unattended mode. The proposed Mars network architecture was examined and enhancements to the architecture were suggested. These enhancements, if added, will improve the fault tolerance of the network via improved connectivity between all nodes. Enhancements suggested included:

- Addition of a third Mars Relay Satellite (MRS),
- Incorporation of crosslink capabilities between MRS's,
- Addition of a Mars Communications Hub, and
- Addition of a Mars Polar Relay Satellite.

Mars network management functions were grouped into one of six categories; Fault Management, Configuration Management, Accounting Management, Performance Management, Resource Management, and Security Management. Technology assessments were then performed in each of these areas to determine what technologies might be needed to limit the astronauts' role at Mars in the execution of these functions. For completeness, it was assumed that all functional areas would be automated at Mars, although in actuality only those critical functions that cannot afford a 40 minute delay will have to be automated. The remaining non-realtime functions could be performed by network operations personnel at Earth. Technologies studied included both conventional and emerging Distributed Artificial Intelligence (DAI) network management technologies as well as satellite fault tolerance technologies.

Finally, a technology development plan was prepared. It was recognized that a network testbedding effort should be initiated to define and test different networking standards, technologies, and approaches; and to determine which might be the most practical and effective for implementation in a Mars network. Such an effort would identify those technologies with promising attributes so that they could be further developed to meet the specific needs of a Mars TNIM system.

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Chapter 1

Introduction

This chapter is organized as follows:

- 1.1 Background on Contract
- 1.2 Statement of Work
- 1.3 Organization of Report

1.1 Background on this Contract

Loral is providing technical support to NASA Lewis Research Center on a task order basis in the general area of defining advanced satellite system concepts, under NASA Contract No. NAS3-25092, *Advanced Satellite Systems Concepts* (ASSC). This report gives the results of the third Task Order, entitled *Unattended Network Operations*.

The general scope and objectives of the Task Order Contract are as follows. Over the next four years (fiscal years 1989–1992), NASA will be evaluating several new advanced satellite system concepts as potential new experimental satellite programs. These are in response to new NASA mission needs as well as responding to specific recommendations of the NASA Advisory Council. These new concepts include:

- Data Distribution Satellite
- Wideband Point-to-Point Communications
- Intersatellite Communications
- Small Terminal Communications

Loral is required to provide personnel and other resources as needed for technical support to NASA for the purpose of aiding NASA in the formulation, evaluation, and advocacy of certain advanced communication satellite applications. Analyses will be performed and results provided as required by NASA for the purpose

of explaining and justifying potential future advanced satellite technology development and flight programs.

To accomplish these objectives, Loral will perform specific tasks that are defined through the issuance of Task Orders to perform any of the following:

- i. Definition of preliminary concepts.
- ii. Sensitivity analyses.
- iii. Identification of critical technologies.
- iv. Formulation of preliminary technology plans.
- v. Preparation of written reports, oral reports, and graphic presentation materials.

1.2 Statement of Work

This section gives the Statement of Work for the Unattended Network Operations Study which is the subject of this Final Report. Background is given together with the Scope of Work which is divided into four subtasks.

1.2.1 Background

One major element needed to accomplish the ambitious goals set forth in the Space Exploration Initiative (SEI) is the Telecommunications, Navigation, and Information Management (TNIM) system. In the past, piloted mission operations, telecommunications, and navigation functions have operated with Earth-based, primarily manual and highly personnel-intensive systems. While direct extensions of these existing system architectures may suffice for the lunar TNIM system, such an Earth-centered manpower intensive system would result in a complex, awkward, and non-responsive TNIM system for Martian exploration phase of the SEI. This is primarily due to the long transmission time between Mars and Earth which can be 20 minutes one way.

However, due to the extreme distances and travel times involved, manpower in the Martian environment will be scarce, costly and would probably better serve mission requirements by performing tasks other than extensive operations of the TNIM system. It is therefore necessary to develop a highly unattended network control mode for mission operations functions. Thus, to enable a responsive Martian TNIM system, in situ adaptive monitor and control TNIM capabilities must be provided.

Since all of our current experience is with attended space networks, in order to avoid a revolutionary change from the lunar to Martian exploration operations environment, it makes sense to evolve this capability utilizing the Moon as a realistic operational test bed. Timing envisioned for the lunar and Mars exploration programs will allow the lunar setting to be utilized in developing and implementing this capability for use on the Mars missions.

The network monitor and control functions are used to:

- i. Plan and schedule network usage;
- ii. Provide real time adaptive network control which can accommodate reasonable faults;
- iii. Multiplex and packetize the data at a system entry point;
- iv. Reconstruct the original data streams at a network mission delivery point;
- v. Extract network configuration and status information as part of the data reconstruction process at each delivery point; and
- vi. Determine radiometric navigation information from tracking data.

Once again, because of the Moon's proximity to the Earth, it is feasible to conduct an exclusively Earth-based network monitor and control function for lunar exploration. However, due to the long transmission time resulting from the extreme distance between Earth and Mars, an Earth-centered Martian monitor and control system could not respond to any short term (i. e., less than 40 minutes) mission operation needs. Consequently, evolutionary approaches to develop the required capability of infrequently attended network operations starting with lunar exploration is to be examined by this study.

Mars tracking and data acquisition functions are similar to those in the lunar architecture, but with three significant differences:

1. The round trip transmission time is up to 40 minutes compared to several seconds for the Moon.
2. The Martian rotational period is a little over 24 hours which causes facilities on the Martian surface to lose direct connectivity with the Earth for 10 to 12 hours per day. This may require relay satellites placed around Mars. In contrast, relay satellites for lunar exploration may only be required when accessing lunar far side regions.
3. The large telecommunications distance from Earth to Mars causes all Mars-to-Earth links to be severely power-limited (resulting in data rate restrictions). In contrast, achievable lunar power levels could telemeter as much data as Earth-based users can utilize.

Due to these factors, Mars telecommunications system must utilize Martian relay satellites, operate primarily at Ka-band (or higher) frequencies, and have telecommunications terminals that operate in infrequently attended modes. The lunar system may initially start operations as an Earth-based attended mode, and evolve to an infrequently attended system which has a fail-soft capability of manual operations from Earth.

1.2.2 Scope of Work

The purpose of this study is:

- a. To explore aspects of network operations for the SEI Mars manned missions that can or should be automated to achieve infrequently attended network operations.
- b. To assess what technology and advanced engineering development is required to accomplish this goal, and
- c. To determine requirements which must be included in the initial lunar SEI TNIM system so that the lunar system can serve as a development and test bed facility for evolution of Martian exploration TNIM.

1.2.2.1 Task 1: Identification of Functions for Unattended Operations

The purpose of this task is to investigate the various aspects of mission operations network control to determine which network operations tasks need to be automated to achieve largely unattended operations for the Mars manned missions of the Space Exploration Initiative (SEI). This would involve consideration of such things as operations of satellite master control centers, NASA mission control operations for manned missions, operations for the TDRS system, and other existing network control facilities which might be applicable to a Mars manned mission network control system.

Network control functions may include such things as planning, scheduling, and controlling the telecommunications navigation, and information management (TNIM) systems, network fault detection and isolation, fault correction which can include dynamic reconfiguration, and other network operation and control functions. This investigation is not bound to current examples and should include new and innovative ideas in the area of mission operations and network control.

1.2.2.2 Task 2: Technology Assessment

Once network operation functions with the potential or need to be automated have been identified, an assessment of alternative innovative system concepts which might affect the technology level needed to implement these functions is to be conducted. Promising systems concepts, those that suggest reasonable implementation and operations approaches, are to be examined to determine the technology and advanced engineering implications of these approaches.

This technology assessment for infrequently attended network operations in the Mars manned mission is to include an examination of those functions identified in Task 1 of this study and a determination of the technology development required, if any, to advance each of these functions to the appropriate level of development required for such an unattended network. Such technology development may target hardware, software, and operations approach and philosophy; or a combination of these areas. This assessment would take into account such things as the necessity and the feasibility of automating functions as well as the time frame in which this unattended network is required.

1.2.2.3 Task 3: Technology Development Plan

The purpose of this task is to provide an estimate of the schedule and funding required to develop the necessary technologies and advanced engineering for use in the SEI Mars manned missions. It may be assumed that the lunar TNIM system could be used as a test bed for these technologies and for the concept of unattended network operations in general.

The schedule and funding estimates should be done on a technology by technology basis. If a given technology is common to more than one area or function, this should be taken into account when developing schedule and required funding estimates. Schedules (i. e., time lines) for technology development should be given on a generic basis rather than assuming a specific starting date for such development. Similarly, funding estimates should be given in constant 1991 dollars without taking into account inflation and should be given on a yearly basis.

1.2.2.4 Task 4: Reporting

The expected product from this study is a final report which documents:

1. Network operations functions that can or should be automated;
2. Requirements that should be included in the lunar TNIM designs to make that system appropriate to be used as a Mars TNIM test bed;
3. Explicit identification of innovative ideas recommended; and
4. Technology assessment of these functions to provide infrequently attended network operations.

The total reporting requirements are as follows:

- Concise monthly progress reports to the technical manager;
- Formal presentation at NASA Lewis Research Center upon completion of this study summarizing the methodology and results of this study;
- Final report as described above.

Table 1-1: Organization of Report

Chapter	Contents
1.	Introduction
2.	Executive Summary
3.	Baseline Mars TNIM Network Architecture
4.	Overview of TNIM Functions to be Automated
5.	Assessment of Network Management Technologies
6.	Technology Development Plan

1.3 Organization of Report

Table 1-1 gives the organization of this Final Report by chapter. Chapter 2 presents an executive summary of the work.

Chapter 3 presents some of the background information that was consolidated and used by the study group over the course of the study. This information helped form a baseline architecture for the Mars network that could be referred to as the study progressed. It has been included in this final report for the reader to reference, as well as to present some new thoughts on how the network architecture could be improved.

Chapter 4 describes a standard set of Telecommunications, Navigation, and Information Management (TNIM) network control functions as required by the SOW Subtask 1, "Identification of Functions for Unattended Operations". Six generic network control functions that would have to be automated in an unattended network operation are described.

Chapter 5 discusses technologies that might be further developed to automate the Mars TNIM functions identified in Chapter 4. This is in response to the SOW Subtask 2, "Technology Assessment". The chapter focuses on two technology areas:

- i. Artificial Intelligence technologies needed for taking man out of the loop in controlling a network;
- ii. Fault tolerant technologies inherent in the design of an unattended network.

Chapter 6 presents a suggested technology development plan. Ideas are given on how an Earth-based testbed for an unattended communications network might be constructed. This testbed could be used to evaluate promising unattended network technologies and concepts that could be integrated into future lunar and Mars communications networks.

Chapter 2

Executive Summary

This chapter gives an executive summary of the *Unattended Network Operations Technology Assessment Study*. Mars network monitor and control functions to be automated are described first, followed by an assessment of the supporting technologies required for unattended operation of the network. Then a suggested testbed development plan is discussed, and conclusions and recommendations for next steps are presented.

2.1 TNIM Functions to be Automated

2.2 Assessment of Unattended Network Technologies

2.3 Technology Development Plan

2.4 Conclusions & Recommendations

2.1 TNIM Functions to be Automated

This section, which is a summary of the material in Chapter 4, addresses the Telecommunications, Navigation, and Information Management (TNIM) network monitor and control functions required to support network communications and navigation in the Mars environment.

2.1.1 Scope and Methodology

The Mars TNIM architecture is not fixed at the present time. The study only assumes that the network may be composed of some combination of the architectural elements discussed in Chapter 3.

Network monitor and control functions covered in this section are common to all network nodes and are applicable to most all network architectures. These functions are used to monitor and control the TNIM network across which telecommunications and navigation information will flow.

The TNIM communications system can be modeled as a collection of sites, each of which represents a distinct distributed location where some type of communications equipment resides. These sites are connected via the Mars Relay Satellites (MRS's) located in Mars-synchronous orbits.

The goal of network management is to maintain user-to-user service under changing traffic conditions, user requirements, and system interruptions. The best use of the resources available to detect and diagnose faults or service degradation must be applied to maintain service to the user. The following is a description of network monitor and control functions needed to meet these objectives.

2.1.2 Description of Mars TNIM Monitor and Control Functions

Integrated Network Management (INM) functions fall into one of six main categories as defined by the International Standards Organization (ISO):

1. Fault management
2. Configuration management
3. Accounting management
4. Performance management
5. Resource management
6. Security management

2.1.2.1 Fault Management Functions

A comprehensive set of functions for fault handling must be provided. These functions include detecting, diagnosing, and recovering from network faults. Since much of the TNIM equipment will be difficult to access, fault handling functions must emphasize early prediction and prevention of faults or automated switch-over to redundant systems.

2.1.2.2 Configuration Management Functions

Configuration management functions include defining, changing, monitoring, and controlling network resources and data.

2.1.2.3 Accounting Management Functions

In order to support the TNIM planning and scheduling functions, the status and availability of network resources must be monitored and maintained. Resource availabilities may vary due to planned outages such as the MRS's being out of Earth view, or due to unplanned events such as equipment failures.

2.1.2.4 Performance Management Functions

Performance management functions include monitoring both the current and long term performance of the network. Parameters to be monitored include effective link data rates, link data quality, time taken for link acquisition, and link down times.

2.1.2.5 Resource Management Functions

Once the high level priorities and policies are defined and the major events planned, TNIM network resources need to be assigned to support them. This will result in a high level event schedule and general resource allocation profile. For example, a general resource allocation might allow Mars inhabitants 4 hours per week on a video link to Earth.

2.1.2.6 Security Management Functions

Security Management Functions ensure authorized access to the network resources and user information.

2.2 Assessment of Unattended Network Technologies

This section summarizes the work presented in Chapter 5. After reviewing current NASA space-based network approaches such as DSN, TDRS, and NASCOM, it has become evident that little has been done to reduce manpower levels in the operations of space-based networks.

Two technology areas were investigated for unattended networks:

1. Network Management Technologies

2. Fault Tolerant Technologies

The first group of technologies were those needed to automate network monitor and control functions. These technologies are required to take man out of the control and decision making loop for routine Mars network operations. As mentioned above, current space communication networks in use by NASA are very manpower intensive in virtually all functional areas (scheduling, acquisition, problem resolution, ...). However, commercial network control systems such as telephone and information systems have seen considerable automation of the processes and functions involved. Some of the supporting technologies and approaches could be applied to space-based networks. Even commercial networks do not run fully unattended – man is still in the loop to handle faults.

A second technological area, fault prevention and fault tolerance technologies, was investigated. Prevention of network faults is highly desirable in any design, but it becomes especially important in an unattended network since the prevention of faults implies prevention of performing the complex decision making and repair efforts that accompany recovery from faults. Much of the decision making will have to be made locally at Mars. Fault tolerance includes fault detection and correction. Inclusion of certain fault tolerant technologies in the system design will allow graceful degradation with time as opposed to sudden and catastrophic failures. The Mars system may have to last 10 to 15 years and quite possibly much longer, at least for the long term missions.

After we are able to develop fully unattended networks on Earth, we can apply the technologies developed to Space Exploration Initiative (SEI) networks where new difficulties arise due to longer distances and higher data rates.

2.2.1 Assessment of Network Management Technologies

The major problem in implementing a distributed communication network system is how to take action at a temporal and spatial distance. For example, when a communications link fails, new routing strategies must be coordinated not only at the nodes involved, but also at additional nodes involved in the alternative routing

strategy. The problem solver must reason about and coordinate the remote effects of local decisions and reasoning with indeterminate knowledge.

The problems are exacerbated as the scale of the system increases. For example, it may not be possible for a node to immediately determine the status of another node or activate it in time to ensure that network connectivity is maintained. Even current world-wide communications systems (e. g. NASCOM) have serious problems with synchronizing and coordinating communications services. These problems can only be expected to increase as we attempt to expand the communications to include lunar and Mars-based communications nodes.

Protocol Approaches for Managing Network Resources

The use of protocols have been widely accepted as an effective means for managing local area and wide area networks in multi-vendor environments. These protocols include:

- Common Management Information Protocol (CMIP),
- Common Management Protocol over TCP/IP (CMOT), and
- Simple Network Management Protocol (SNMP).

The most widely accepted and used protocol is the SNMP.

There are two components to the implementation of SNMP; an agent and a network management station. The agent is software found on a variety of network elements (bridges, routers, file servers, etc.). The agent collects network statistics for the element on which it resides. The agent forwards the information when requested by a network management station or when an event occurs. Other network monitor and control tasks include evaluating the status of various network elements, reviewing error situations, and dynamically rerouting network traffic around network nodes which are heavily loaded. Due to its message passing and distributed topology, the SNMP has a design framework which lends itself to implementing a Distributed Artificial Intelligence (DAI) system.

2.2.1.1 The Role of Distributed Artificial Intelligence

Distributed Artificial Intelligence (DAI) is a branch of the AI discipline dealing with the cooperative solution of problems by a distributed and decentralized group of agents. The agents can be simple or complex processing elements.

DAI deals with problems that develop when a group of loosely-coupled problem-solving agents cooperate to solve a problem. In such a problem-solving environment, each of the agents has a limited amount of knowledge of the problem and can only gain this knowledge through communication and coordination with other agents. DAI falls into two categories:

- i. Distributed Problem Solving (DPS)
- ii. Multi-agent systems

By combining conventional software problem solving techniques with emerging AI technologies, DAI is able to solve complex problems in a distributed environment. In a telecommunication network, by applying a framework similar to the SNMP, the status of each element or node on the network can be monitored and any faults can be detected with conventional software or hardware technologies. Judicious selection of AI and conventional methodologies can be employed to manage the faults.

Modeling and simulation techniques can be employed to monitor the performance of the processing elements within the network. The performance information will help in identifying the constraints within the network. The information about the network constraints can then be used for managing the resources within the network.

The following are some of the benefits of Distributed Artificial Intelligence:

- Inherent parallelism in the approach speeds up computations and problem solving.
- Reliability and survivability is improved through redundancy.
- Helps to achieve increased modularity and reconfigurability.
- Accommodates open systems (systems with no complete representation and with dynamically changing boundaries).

- **Adaptability:** concurrent systems are inherently more adaptable than sequential systems.
- **Multiple perspectives:** different problem solvers can bring several perspectives to bear on one problem.

2.2.1.2 Fault Management Technologies

AI technologies such as diagnostic expert systems and artificial neural systems can be used for detecting, diagnosing, and correcting network faults. There are currently many excellent off-the-shelf software packages that provide adequate functionality to support development of robust AI fault management systems.

For simple subsystems, rule-based systems with predictably robust performance are easy to develop, but complex systems often require more powerful strategies such as model-based reasoning paradigms. Model-based expert systems use an internally defined model to reason about the system, both to trace causal relationships and explore possible corrections strategies. Hybrid approaches often prove to be the most workable and effective systems.

Artificial neural systems provide excellent means (learning paradigms and models) for detecting errors and classifying errors (diagnosing). Their principal benefits are the ability to provide robust response over widely varying conditions, the ease of programming (training) them to handle new situations, and their capability to provide real-time response once trained.

A combination of the use of artificial neural systems and expert systems is ideal for fault management. Recovery from network faults can be represented as a set of rules which will operate on the results from the Artificial Neural System (ANS) and model-based reasoning systems.

2.2.1.3 Configuration Management Technologies

Configuration management is a prerequisite for effective application of the other elements of network management. The data base of all network components (e. g., hardware, software, circuits or lines) must be made available to help in scheduling and tracking of changes to the configuration.

Techniques for Configuration Management. One approach using a hybrid rule/frame-based methodology can apply a set of rules that specify what a complete or

legal solution must include when presented with a set of initial choices from among a set of options, with implications or constraints. It must also apply some conflict resolution rules to arrive at a legal solution.

A machine learning technique can be developed and trained with a certain set of examples to recognize patterns and thereby learn how to configure the network when certain patterns appear in the system. Such an adaptive system is better than a rule based system which will demand that new rules be developed when new situations which have not been represented in the rule base occur. Also, there may be too many rules to write. For an unattended network system, an adaptive system is highly recommended.

Case-based reasoning systems can be applied in configuring a communication network system. If a knowledge of possible cases exists, then by using a library of past cases the system can reconfigure the network autonomously.

The monitoring part of configuration management can be performed by:

- i. Backward-chaining, rule-based diagnostic expert system which runs repeatedly until a particular recommendation is encountered and then alarms appropriate embedded system, or
- ii. Forward chaining system that monitors data patterns and informs the controlling function when a particular pattern is encountered.

2.2.1.4 Accounting Management Technologies

Data being generated at different nodes of the network will need to be buffered and retrieved in an efficient manner and in a form understood by a client agent. It is necessary to investigate efficient data acquisition, storage and retrieval technologies for managing the information. A combination of a conventional approach to data management and object-oriented database management technologies should be investigated to handle data generation at each node and data distribution to requesting agents within the network.

2.2.1.5 Performance Management Technologies

Performance management technologies measure and analyze resource utilization and network response time. They provide engineering traffic statistics to aid in predictive network performance.

Recommended solution approaches may include conventional discrete event simulation technologies and knowledge-based simulation techniques. Application of object-oriented knowledge representation schemes will aid system modularity and extensibility.

2.2.1.6 Security Management Technologies

Technologies that guarantee the correct coordination of the agents (software) are required for preventing incorrect activation and execution of other agents. These technologies are necessary to ensure a secure and reliable system.

2.2.1.7 Resource Management Technologies

For small and simple tasks, forward chaining rule-based expert systems or operations research techniques (linear programming) can be used. For mid-size or large and complex resource management tasks, the use of hybrid tools (object oriented and rule-based reasoning) are necessary.

2.2.2 Assessment of Fault Tolerant Technologies

A key issue which was identified in this study was the extent to which the network should be fault tolerant. The TNIM system must provide significant levels of fault tolerance both at the system subsystem and component levels to achieve its mission. This is driven by a number of considerations:

- Minimal availability of manpower and resources at Mars or in Mars orbit to repair malfunctions.
- Limited capability for remote diagnosis due to the difficulties of Mars-Earth communications (time delay, pointing, bandwidth).
- Critical support requirements during maneuvers such as aerobraking and launch.
- Long mission life including both transit from Earth to Mars and on-site and on-orbit at Mars.
- Need for man-rated reliability during the later phases of the Space Exploration Initiative (SEI).

Most importantly, the long journey time between Earth and Mars and the remoteness of the Mars location dictates that all SEI subsystems be engineered so

that they are immune to multiple failures or that mission objectives can be safely carried out in the face of significant loss or degradation of component functions. This requirement is even more critical than previous missions such as Mercury, Apollo, Skylab, or the Shuttle flights since SEI missions will be inherently longer in duration.

The fault tolerance technologies study dealt with both system and component level technologies required to achieve the above goals. Its objective was to understand the potential failure modes of TNIM equipment, particularly communications satellites and unattended switching equipment, and to describe technologies which must be developed to improve potential fault tolerance of TNIM systems.

As part of this study we conducted a literature search of existing methods for fault tolerant systems engineering and interviewed Loral satellite operations personnel familiar with communications satellite failure modes. Within the resource limits of the study we attempted to collect information about existing communications satellite systems and their failure modes, and the approaches that have been used by both deep space missions and DoD survivable satellite programs where autonomous fault tolerance are critical mission requirements. We also studied a number of NASA, DoD, and commercial communications programs with significant reliability and fault tolerance requirements.

A fifteen-step process based on existing NASA and DoD reliability engineering methods was identified. The initial steps of this process were followed to identify potential sources of failure at the system level and at the subsystem level in the most critical and least serviceable TNIM component, the Mars Relay Satellites (MRS's).

The potential failure modes of the MRS's were determined and characterized by subsystem and time in the launch, deployment, and maintenance life cycles of the satellite. This analysis was derived from existing operational knowledge of earth-synchronous communications satellites.

For each potential subsystem failure, key technologies which might reduce system failure probability were identified and described in tabular form (Table 5-3). Four key areas are identified as critical and analyzed in detail; (1) attitude control, (2) communications, (3) power, and (4) data recorders.

The following technology areas are identified as key areas for the development of fault tolerant technologies

in support of TNIM:

- Intelligent control systems, particularly for spacecraft attitude and power.
- Reliable, high-power (≥ 50 W) Ka-band rf power amplifiers.
- Space-qualified data recording systems with reduced number of mechanical parts.
- Fiber optics and micro-mechanical components for inertial reference units.
- Reliable Earth, Mars, sun, and/or star sensors with reduced mechanics.

Moreover, it is recommended that a comprehensive set of fault tolerance goals should be established for TNIM. At the earliest possible point, a system-level approach for TNIM fault tolerance should be established to guide subsystem design and technology development effort. We believe that the issue of fault tolerance and reliability for TNIM systems requires substantially more study than was feasible within the resources of this study.

2.3 Technology Development Plan

In this study we present a plan for developing the necessary technologies for unattended telecommunications network management. We recommend the development of a testbed for (1) using new technologies and innovative use of existing technologies to determine optimum performance approaches for implementing Mars unattended communications networks and for (2) demonstrating the feasibility of applying these technologies to the Mars mission requirements.

We divide the development of this testbed into the following stages:

- i. Initial simulation and modeling
- ii. Earth-based networking
- iii. Lunar operations
- iv. Preliminary Mars-based operations

2.3.1 Testbed for Managing Network Resources

We proposed that NASA fund an effort to create an integrated testbed which would initially utilize Simple Network Management Protocol (SNMP) concepts to model agent and network components of a series of TNIM architectures. Initial modeling would take place within a single workstation with software processes designed to simulate TNIM nodes and links. Such a simulation would be highly parametrized and include specific software elements to model communications delays and outages based on orbit geometry and known models of deep space communications interference. Specific faults and communications loads could be introduced into the model and the performance of the model under various conditions could be monitored and analyzed.

The initial strategy would be to purchase an off-the-shelf network management package based on SNMP and insert software elements which would support detailed modeling of TNIM nodes, links, and management functions.

2.3.2 Objectives of the Testbed

The proposed test-bed would have the following objectives:

- Identify candidate TNIM distributed network management architectures and provide preliminary estimates of network performance under anticipated communications scenarios.
- Test the performance of routing protocols and their ability to provide connectivity and dynamic response to network loading.
- Identify and test strategies for routing network traffic under both routine link interruptions and equipment failure.
- Support an iterative process of discovery of new TNIM network management requirements through experiment, observation, and analysis.
- The proposed test-bed would serve to support the investigation of the effectiveness of tools for DAI in unattended communications network applications.

2.4 Conclusions & Recommendations

The primary conclusion of this study is that there is a great deal of technology available for unattended network operation that has not yet been applied to manned space networks. Current communications and navigation networks used to support manned space missions are extremely manpower intensive, far more so than is necessary with current technology. Much automation of these networks must be done before they can be used to support manned operations over the long distances to Mars.

Implementation of the following recommendations could reduce the magnitude of technology gap between what is presently available commercially and what is used for NASA space communications. Implementation would better prepare NASA for future manned space exploration initiatives.

- Develop a comprehensive set of fault tolerance and fault prevention objectives for future NASA communication networks.
- Study, develop, test, and implement TNIM fault tolerance technologies as they apply to plans for future NASA space-based communications systems.
- Develop a comprehensive set of network management objectives and standards for future NASA communication networks.
- Study, develop, test, and implement new network management technologies as they apply to plans for future NASA space-based communications systems.

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Chapter 3

Baseline Mars TNIM Network Architecture

Several Mars Telecommunications, Navigation, and Information Management (TNIM) architectural issues had to be resolved prior to defining the TNIM functions to be automated. Contained in this chapter is the background information compiled by the study group while forming a baseline TNIM architecture to work with. While the information contained in this chapter was not specifically requested, it was thought that inclusion of this background information might aid the reader as an additional reference. Individuals already familiar with the Mars TNIM architecture proposed in NASA's 90 day study [1]¹ may wish to proceed to Chapter 4.

This chapter is organized as follows:

- 3.1 90 Day Study Architecture
- 3.2 Proposed Baseline Enhancements to the Network
- 3.3 Resulting Line-of-Sight Visibility and Redundancy Between Enhanced Nodes
- 3.4 Possible Data Transmission Methods for Mars Network
- 3.5 References

3.1 90 Day Study Architecture

The 90 Day Study provided several baseline approaches for Lunar/Mars exploration. These were referred to as reference approaches 1 through 5. These baselines for mission requirements were modified and focused to respond to updated requirements for two mission options, 1 and 5. A preliminary Telecommunications, Navigation, and Information Management (TNIM) architecture was developed to meet the combined requirements of options 1 and 5. This preliminary network architecture depicted in Figure 3-1 would be in place to support

TNIM functions for unmanned robotic reconnaissance and manned operations on the Moon and Mars.

3.1.1 Preliminary TNIM Architecture

A single Lunar Relay Satellite (LRS) in halo orbit about the lunar L2 libration point would enhance communications and navigation coverage at the Moon by providing Lunar far side visibility that could be used to support communications with astronomical observatories and rovers.

Initially, Mars Relay Satellites (MRS) located in areosynchronous orbits about Mars would support unmanned surveying missions such as a Mars site reconnaissance orbiter and surface rovers. The MRS's will provide telecommunications relay support as well as radiometric navigation support to all users.

As the 90 Day Study points out, placing the MRS's in areosynchronous orbits would greatly improve connectivity between points on the Mars surface and the Earth.

The use of two MRS's located as seen in Figure 3-1 would give 24 hour/day coverage between the Mars habitat (located in view of both relay satellites) and the Earth. This does not include the outages that occur during solar conjunction when the Sun, Earth, and Mars line up radially. It has been assumed that manned missions to Mars would be scheduled around periods of solar conjunction which will occur about every 13 months and last for about one week.

MRS's also provide improved Mars local communications visibility. A non-synchronous relay satellite will not provide continuous connectivity between surface users at Mars. Also, the line of sight direction between Mars surface users and the MRS's remain constant assuming the areosynchronous orbits are properly maintained. This means surface user antenna pointing and scheduling systems will be greatly simplified since MRS antenna pointing will be fixed relative to the user.

¹ References are given at the end of the Chapter.

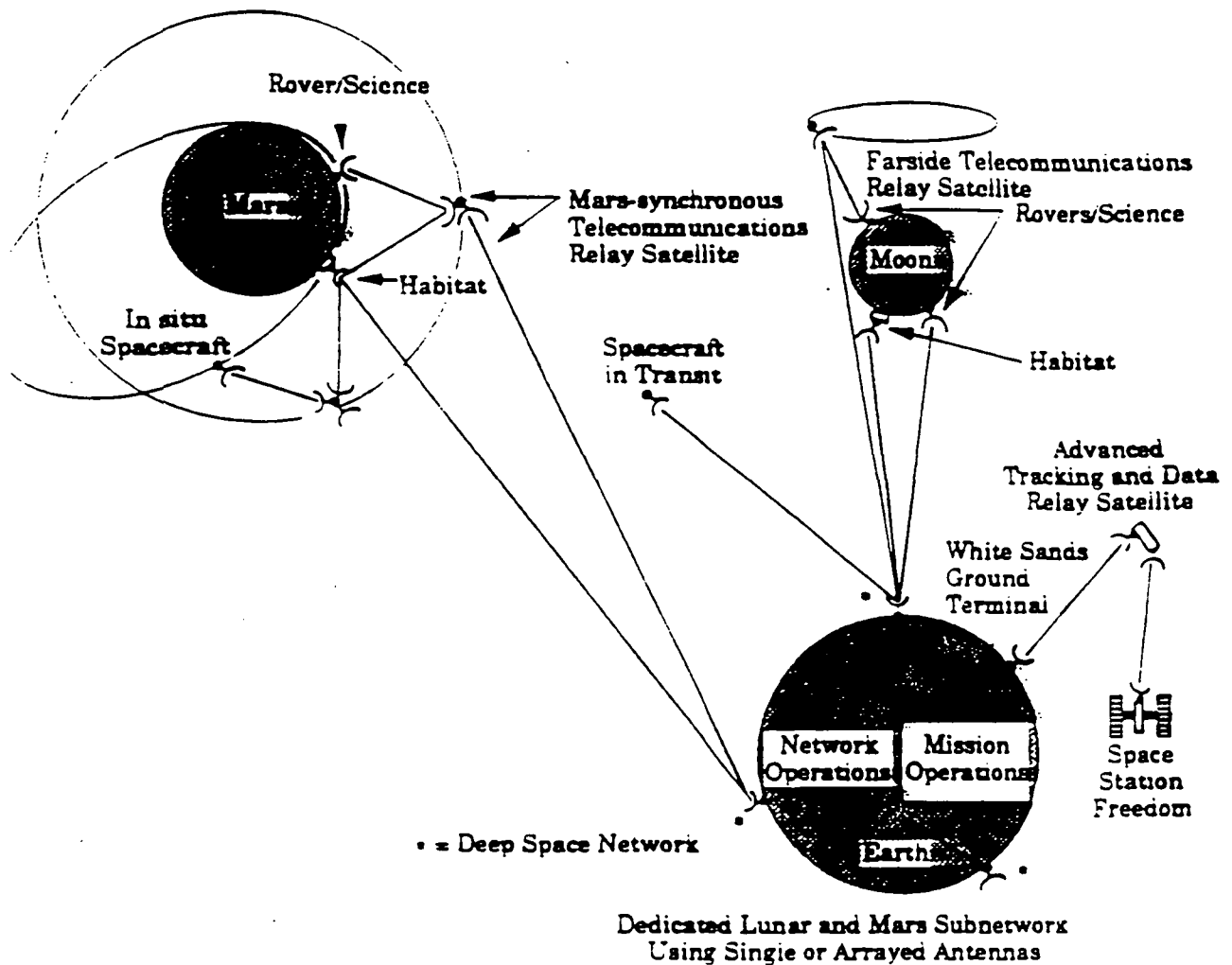


Figure 3-1: 90 Day Study Telecommunications, Navigation, and Information Management Architecture

The MRS proposed would support communications along four different paths including:

1. Mars surface user to Earth
2. Mars orbiting user to Earth
3. Mars surface user to surface user long distance
4. Mars surface user to Mars orbiting user

These communications paths are represented in Figures 3-2 through 3-5.

3.1.2 Key Requirements and Challenges

The 90 day study pointed out several key requirements and challenges the Mars communications network will present.

1. Network must run unattended at Mars. TNIM functions should therefore be performed in the absence of man at Mars.
2. Network must provide fault tolerant system connectivity for all links.
3. Network must provide 90% connectivity with the manned habitats and 98% of scheduled transmissions.
4. Maximum data rates for Mars to Earth transmissions will reach 10 Mb/s for compressed, high rate video transmissions.
5. Maximum data rates for Mars local transmissions will reach 50 Mb/s to support rover telerobotics.

This study concentrated on the evaluation of items 1 through 3 above. We examined the network func-

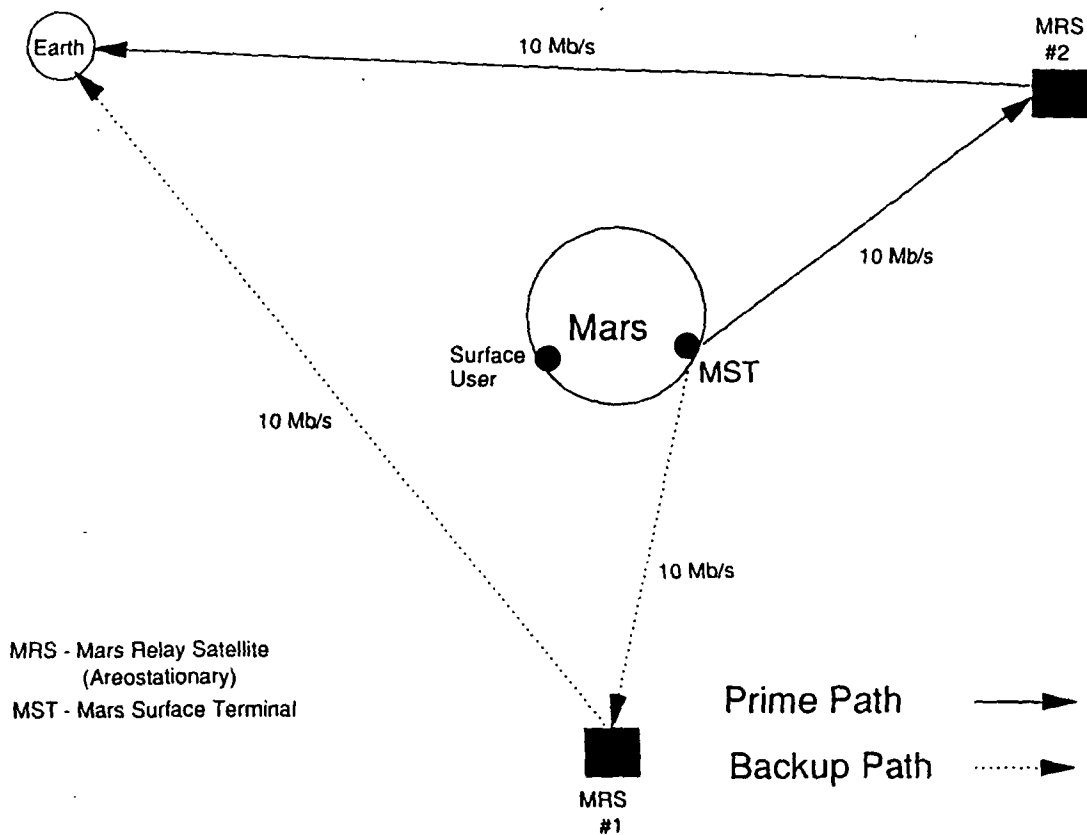


Figure 3-2: Mars Surface User to Earth Path

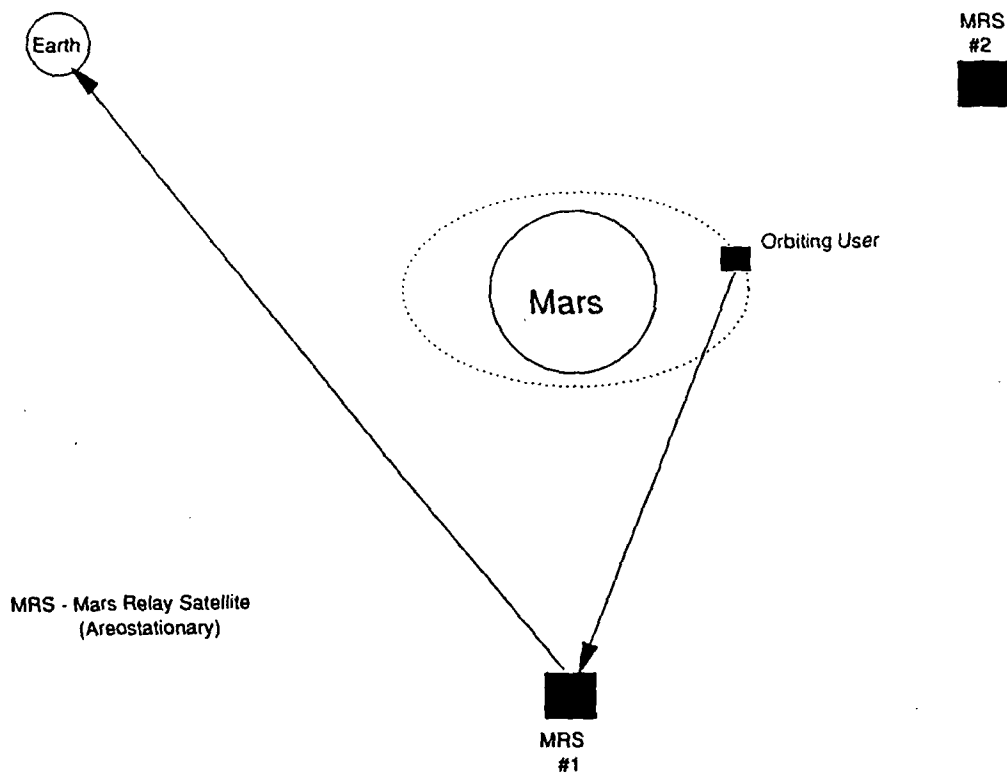


Figure 3-3: Mars Orbiting User to Earth Path

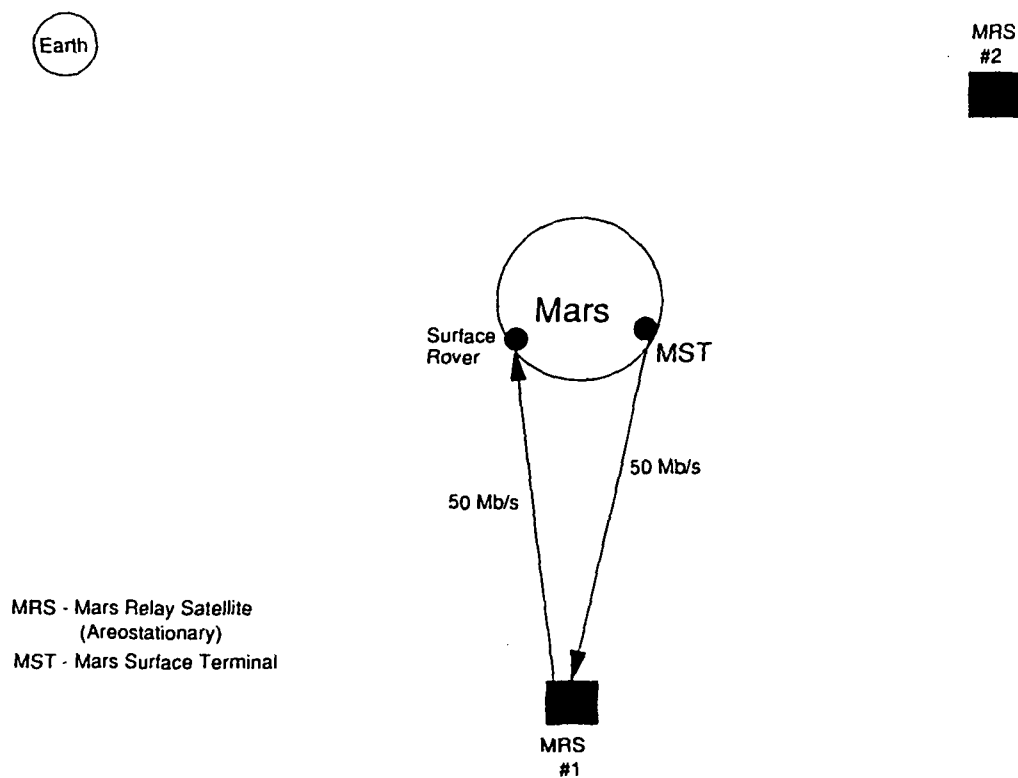


Figure 3-4: Mars Surface User to Surface User Path

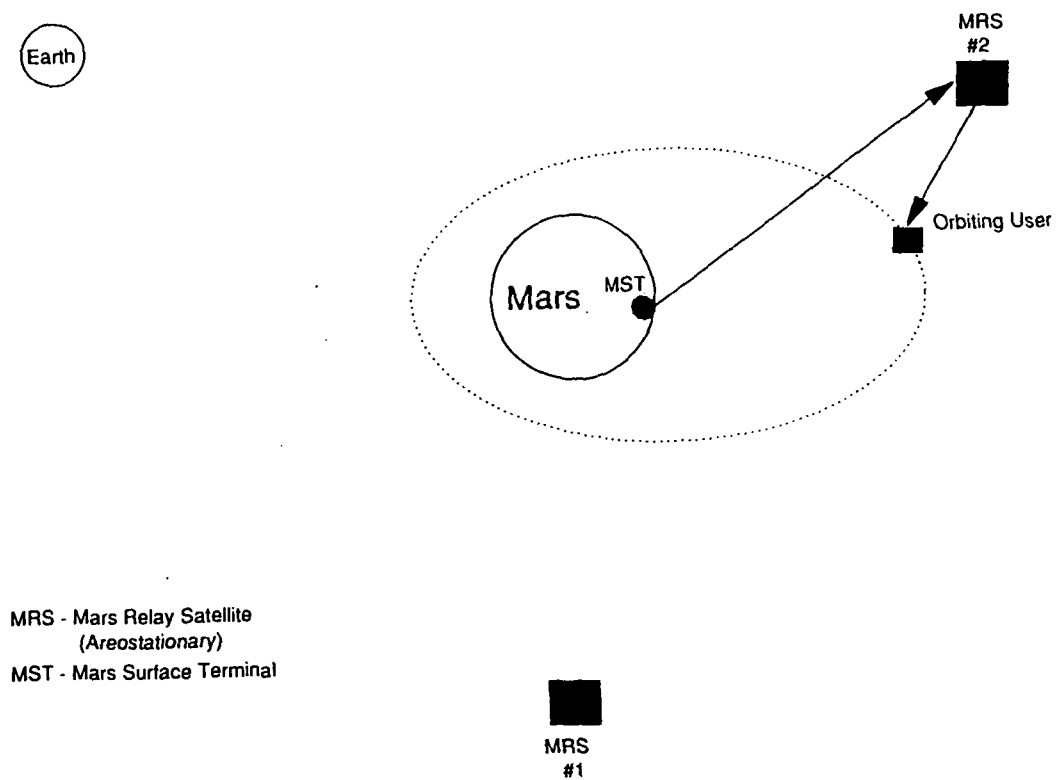


Figure 3-5: Mars Surface User to Orbiting User Path

tions that could be automated and how they might be made fault tolerant while satisfying the connectivity requirements. Technologies needed to provide high Earth/Mars data rates (items 4 and 5 above) were assumed outside the scope of the study.

Needless to say, the key challenges listed above are all interdependent. Satisfying the high Earth/Mars and local data rate requirements adds complexity to the communications systems by the use of state-of-the-art hardware and software. Unfortunately, state-of-the-art communications hardware may not be as reliable as older, proven, communications equipment.

While the two-MRS network proposed in the 90 day study will provide near 100% connectivity between Earth and the manned habitat, it would not provide visibility to the far side of Mars nor would it provide sufficient system level fault tolerance. For this reason and others, several enhancements to the network were considered that provided better connectivity; improved surface and orbit visibility; greater redundancy; and hence, improved fault tolerance.

3.2 Proposed Baseline Enhancements to the Network

Prior to examining the network management technologies required to support unattended Mars TNIM operations, several optional network enhancements were considered for incorporation into the Mars Network design. While the two-MRS design satisfied the minimal requirements for connectivity with Earth and the local Mars environment, it left few options for an unattended fault management system should one of the two MRS's become disabled.

In addition, this system would not provide communications or navigation support to scientific instruments or manned outposts above 75° latitude or to the far side of Mars.

For these reasons the following network options or enhancements were considered for possible inclusion into an unattended, fault tolerant network at Mars :

Incorporation of crosslink capabilities.

Adding crosslink capability to the MRS's greatly enhances the network's path redundancy by permitting an MRS not in view of both the sending node and receiving node to relay the signal to an MRS that can complete the connection. This feature combined with a third MRS (discussed below)

provides users with redundant paths for communications that can be used to either double transmission rates or provide backup communications should an MRS fail.

Addition of a third MRS. Adding a third Mars Relay Satellite (MRS) would provide habitat connectivity with the far side of the planet by providing coverage of the entire Mars surface excluding the poles. In addition, when coupled with crosslink capabilities, the manned habitat as well as other users may exercise the third MRS as part of a backup link either to Earth or to other points on the Mars surface.

Addition of a Mars Polar Relay Satellite (MPRS).

Adding an MPRS to the network will provide regular communications and navigation coverage at the north and south poles of Mars. These polar regions are not visible from synchronous altitude and would therefore have to relay information back to the manned habitat or MRS via an MPRS.

Addition of a Mars Communications Hub (MCH).

An MCH located at the manned habitat could provide additional transmit and receive capabilities with Earth through the use of its own communications system. The MCH could then operate even if both MRS's in view of the manned habitat should fail. This would provide a manual backup capability to the astronauts.

The MCH could also serve as a concentrator of Earth/Mars communications, reducing the complexity of the MRS design in terms of communicating with Earth. The Earth/Mars link would essentially be controlled from this single location as opposed to distributing the control to each of the MRS's. This use of the communications hub would give the astronauts the potential to take corrective action in controlling the Mars network should its automated operations fail.

Figure 3-6 shows the resulting Mars network architecture. This figure excludes the MPRS which if drawn would have its orbit plane perpendicular to the page. The shaded regions on Mars correspond to regions that have redundant MRS coverage. These regions are each about 30° wide at the equator with the exact angular width dependent on how close user's links can approach the Mars horizon.

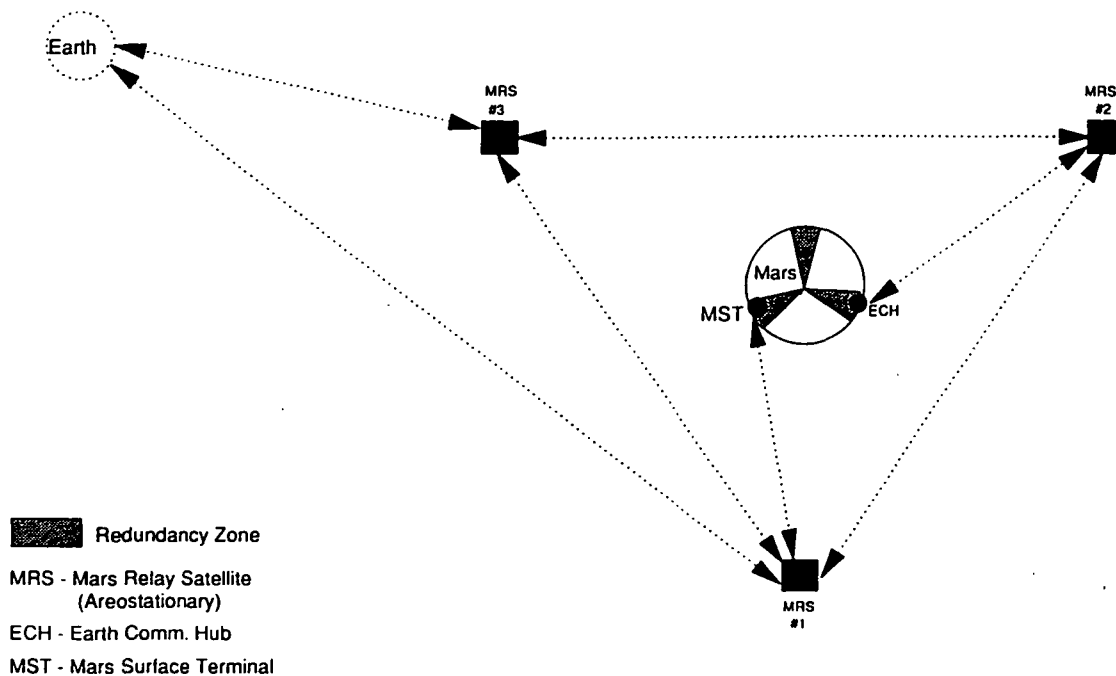


Figure 3-6: Enhanced Mars TNIM Network Architecture

3.3 Resulting Line-of-Site Visibility and Redundancy Between Enhanced Nodes

The Line-Of-Site (LOS) visibility between nodes resulting from a Mars communications network that incorporates the previously mentioned enhancements would more than meet the connectivity requirements presented in the 90 Day Study. This over-designing of the network provides a built-in system redundancy that will greatly enhance the fault-tolerant qualities of the system while at the same time expanding the surface coverage to include the far side of the planet and Mar's poles.

Redundant links between Mars and Earth can also be used to double the data rates from Mars to Earth by transmitting through both paths simultaneously. Arrayed 34 meter DSN antennas will be capable of receiving data simultaneously from multiple MRS's at different frequencies. In the case optical communications would be used, an Earth Relay Satellite (ERS) would have the capability to receive optical signals transmissions from different MRS's simultaneously.

The resulting Earth/Mars communications visibility can be summarized as follows:

1. Every point on Mars surface below 75° latitude and above -75° latitude will be in view of one MRS at all times. This MRS may or may not be in

direct line of site (LOS) of Earth but it will be in LOS of both other MRS's.

2. Some areas on the Mars surface will see two MRS's at all times. These areas can be divided into three regions equally spaced around the equator, each about 30° wide in longitude (see Figure 3-6). We shall refer to these regions as redundancy zones.
3. MRS locations in Martian sky will be fixed relative to surface users if MRS orbits are maintained properly.
4. MRS No. 1 and No. 2 positioning will be such that the redundancy zone between them will include the manned habitat. Consequently the habitat will be in view of both MRS No. 1 and No. 2 at all times. One or both of these MRS's will be in view of the Earth at all times except during solar conjunction when neither MRS will be in view of the Earth.
5. A second independent path for MCH to Earth communications will be possible at all times for users in the redundancy zones. If both MRS's are in view of Earth then a redundant communications path can be utilized to communicate through both MRS's simultaneously to Earth, doubling the effective Earth/Mars data rates. The second path

could also be used as a hot backup should the primary fail.

6. If one of the two MRS's in view of the redundancy zone has its view of Earth occulted by Mars, it can use its crosslink capability to relay data to MRS No. 3 and back to Earth.

3.4 Possible Data Transmission Methods for Mars Network

The following sections are provided as background material regarding the various data transmission approaches that might be used for Mars TNIM data transmissions.

3.4.1 General Approaches

Mars Relay Satellites (MRS's) will be used to establish the communication links described in the previous paragraphs. It is assumed that the final configuration will have the capability to do crosslinking between satellites.

This configuration depicts a constellation of three MRS's equally spaced in synchronous orbit around the planet Mars. Each MRS can see a user group. These user groups can communicate with each other through a crosslink with the adjacent satellite.

Each MRS will be equipped with three sets of antennas:

- i. One points towards planet Earth;
- ii. Another points towards Mars and Mars low-orbiting spacecraft; and
- iii. A third set looks to the second and third MRS.

The MRS antenna pointing towards Mars will have a 3 dB footprint covering about one third of Mars' surface. Furthermore, this antenna will support multiple beams of smaller beamwidths and will be steerable. The crosslink and Earth pointing antennas will be parabolic and steerable.

In the MRS, the communications paths can be established through a bent pipe approach or through an on-board switching approach. The bent pipe approach will allow signals to be routed to their destination via the satellite at RF without processing. The on-board switching approach provides demodulation, signal processing, and signal routing via an intelligent switch on-board the satellite.

3.4.1.1 Bent Pipe Approach

In the bent pipe approach, communications links can be implemented using the standard access techniques commonly applied in satellite communication systems. Considering the volume of traffic, the need for autonomous operations, and the complexity, the primary candidates are as follows:

- Single Channel Per Carrier (SCPC)
- Time Division Multiple Access (TDMA)
- Frequency Division Multiple Access (FDMA)

Figure 3-7 shows a bent pipe model. This model can be appropriately applied to any of the above communication techniques. The MRS will contain transponders and antenna control equipment. In this system, there is no demodulation of the communication signal and no switching is involved.

Except for some station keeping and antenna pointing on the Mars-to-Earth and the low orbit Mars communications links, the communication operations are independent of the Mars habitat. Each user node or user group would be assigned a transmit and associated receive frequency. The user paths can be established through separate receive frequency chains or through techniques utilizing frequency tuning and scanning.

For a user-to-user path for a user group within the footprint of the local areosynchronous satellite, the user information would be modulated and transmitted on an assigned carrier frequency to the satellite. This signal will then be translated and broadcasted to the Mars surface to a terminal tuned to the translated frequency. In the case where the user group is not within the footprint, communications will be established through the crosslink.

The three access techniques which can employ this model are discussed in the following paragraphs.

Single Channel Per Carrier (SCPC). The assigned carriers are translated at the satellite, and simultaneously retransmitted back to the local user's group on Mars, crosslinked to the adjacent satellites to be transmitted to Mars, and/or transmitted to Earth. On Mars, the destination node will have a receive chain tuned to the translated frequency.

For duplexing, the reverse process (from the destination) happens simultaneously. The communication to and from Earth will utilize a designated

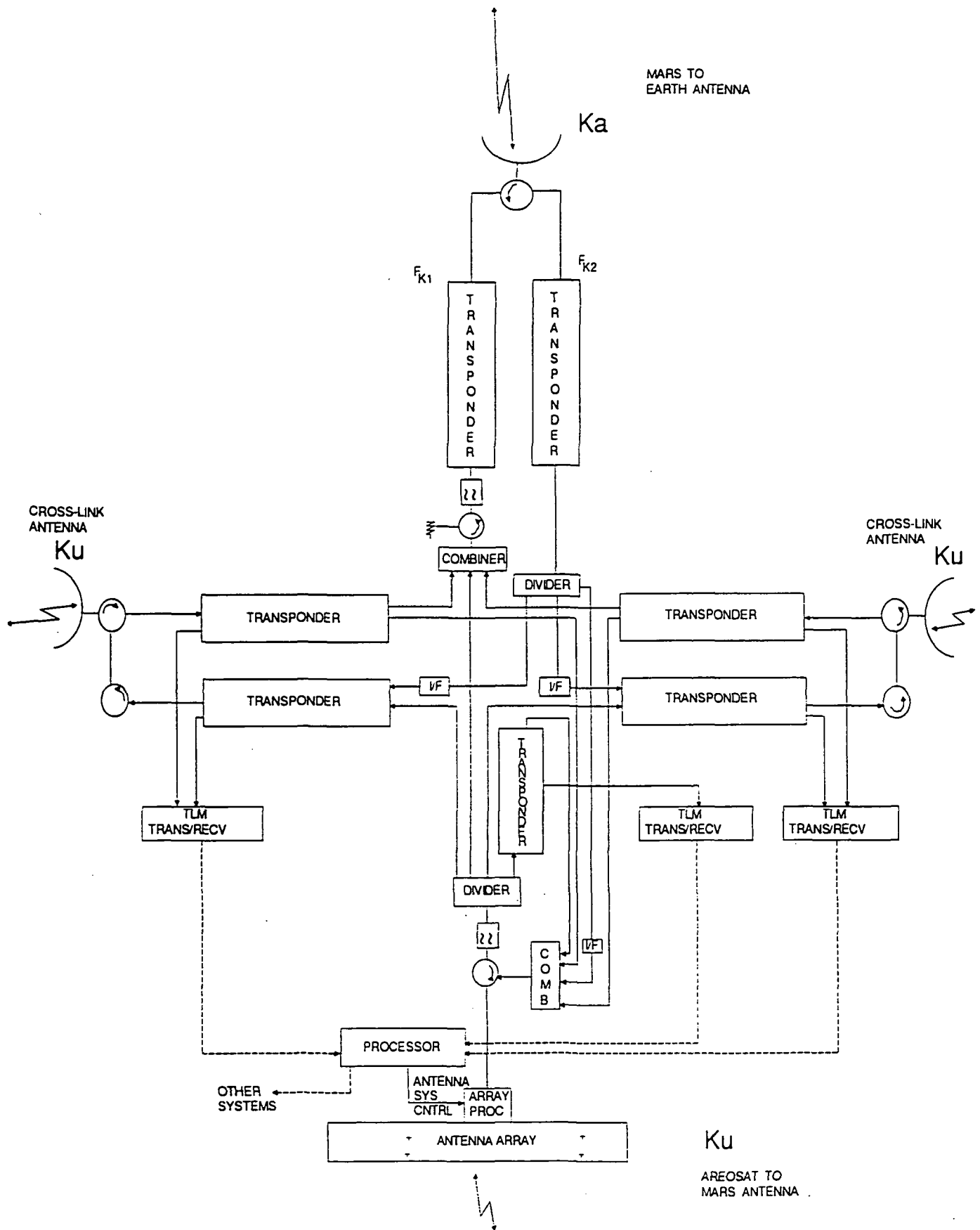


Figure 3-7: Bent Pipe Communications Model

frequency set. The data transmitted can be either digital or analog. Careful frequency planning is required in this mode of operation. Each user must be assigned a separate carrier frequency, and the Mars-to-Earth communications band set aside separately.

Frequency Division Multiple Access

(FDMA) employs multiple channels on subcarriers which in turn are modulated onto a single RF carrier. When this scheme is used in the bent pipe configuration, all the users on the network receive the same RF signal from the sending station. In order to communicate with the sending station, the receiving station must acquire the carrier, downconvert it, and demodulate the subcarrier signal to obtain the data. In this scheme a set of subcarrier frequencies are designated for each communication channel. On most satellite communications paths on Earth, FDMA is used for relatively narrow band communications and for medium to high data rate services.

Time Division Multiple Access (TDMA). Only one transmit and the companion receive frequency are used. This type of communication system requires a reference site, a time burst plan for the user on the network, and a closely grouped user set. The key to successful operation is synchronization of the time slot available to the user. Large time allocation translates to more data transmitted over the total transponder bandwidth.

Because of the delay incurred in the link between areosynchronous satellites, it is not practical to have a TDMA network outside of the area covered by one satellite.

The delay relative to the round trip reference channel delay can not exceed the frame length of the TDMA burst plan. This technique will have its principal application local user group communication cases. Since the TDMA system uses only one carrier frequency, the transponders can operate at saturation with no intermodulation effects.

3.4.1.2 On-Board Switching Approach

In the on-board switching mode, communications links can also be implemented using SCPC, TDMA, and/or FDMA techniques. Figure 3-8 shows a switching configuration model for the Mars Relay Satellite (MRS).

The switching system, however, will include functions such as demodulation, modulation, signal processing, and switching. Additional functions that can be included are forward error correction, and data driven signal routing. On-board equipment health and monitoring operations is an added complexity.

In the On-Board Switching model, the carrier is downconverted, demodulated, and then processed at baseband. In the baseband processing, the traffic would be sorted out by intended destination, rearranged for transmission, and then switched to the designated RF carrier, and retransmitted to its destination.

The processing hardware can include transmultiplexers, forward error correctors, signal regeneration, data buffers, and switches, and multiplexers. In this model all data information will be in blocked format having both header and error control segments for routing and control. The processor will be designed to process data in various standard formats.

The three techniques which can employ this model are discussed in the following paragraphs.

Single Channel Per Carrier (SCPC). The single carrier is downconverted, demodulated into data streams, the data headers read, the errors corrected, and the data routed through a matrix switch to the proper transmission path. At this point the data is multiplexed with other data having the same destination, modulated onto a carrier and routed to the proper destination.

If the destination is a user node on Mars, that node will receive the assigned carrier, demodulate the signal, and receive the information. This process will work in either the simplex or duplex mode. If the destination is on the planet Earth, the data may be multiplexed with other data information before being transmitter to its destination. This model is appropriate for a high data rate users.

Frequency Division Multiple Access (FDMA). In the on-board-switching satellite, signals in the frequency division multiple access mode would be demodulated and processed at baseband. In the FDMA mode, the ground based user data will be modulated onto the subcarrier or subcarriers designated for the receiving parties. The subcarrier in turn will be modulated onto the RF carrier and transmitted to the satellite.

Each set of transmit and receive subcarriers will be designated for a specific communications path. In

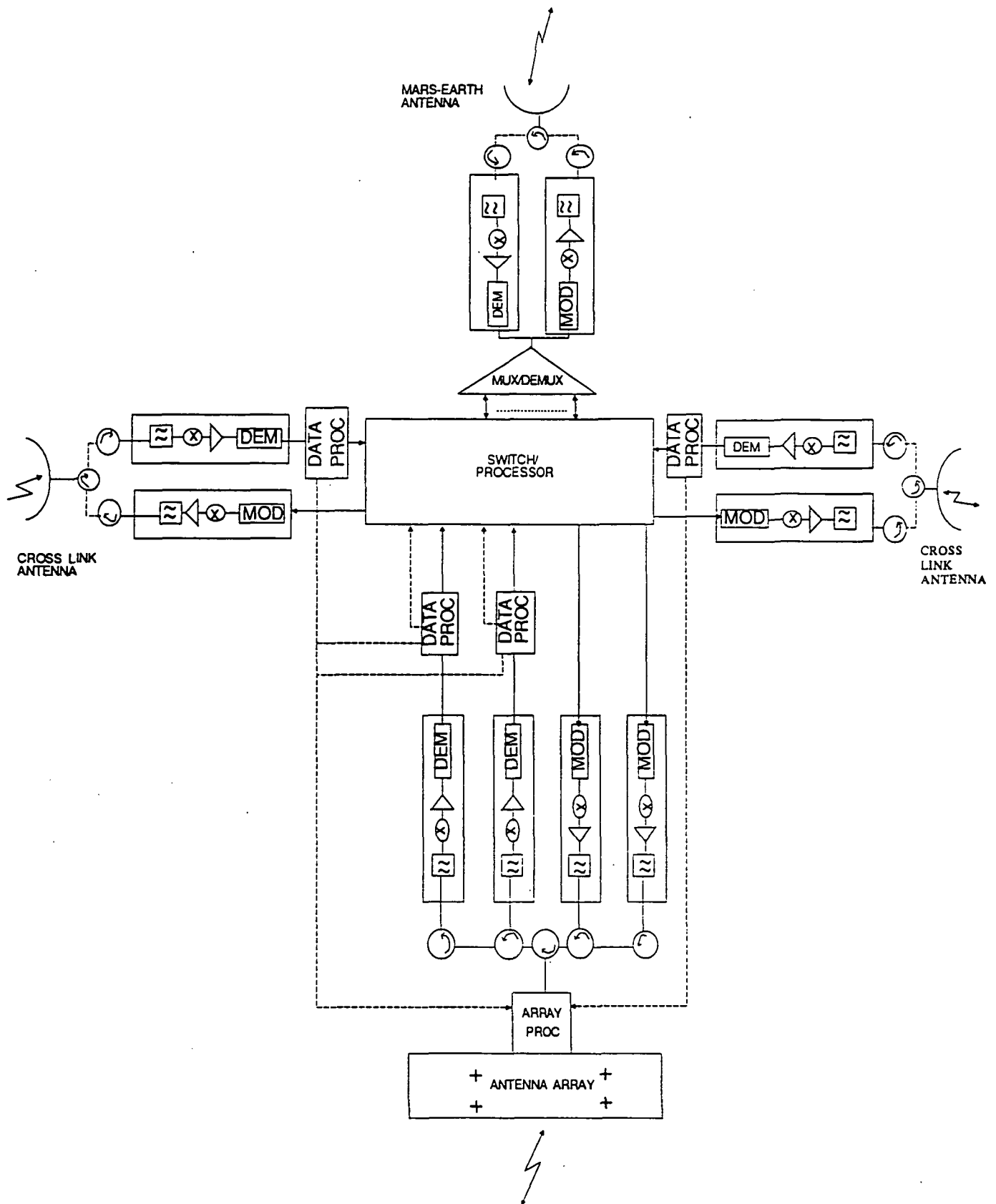


Figure 3-8: On-Board Switching Communications Model

the satellite, the FDMA carrier will be downconverted, demodulated by the receiver, processed by the transmultiplexer, and routed by the data driven switch. In the on-board switching and processing capability, data from all sources can be multiplexed onto a single carrier and transmitted to the designation.

Time Division Multiple Access (TDMA). Only one transmit and the companion receive frequency are used. This type of communication system requires a reference site, a time burst plan for the user on the network, and a closely grouped user set. Because of the delay incurred in the link between MRS's, it is not practical to have a TDMA network outside of the area covered by one satellite. In the On-board switching model, the TDMA will utilize the switch to direct data bursts to spots on Mars surface via the multiple beams of the antenna.

3.4.2 Data Routing Protocols

In the transmission methods discussed, the efficient means of establishing connectivity and communication with the receiver is by the application of layered architecture. There are two basic levels of protocols that are appropriate for the transmission methods described.

- One is the transmission and data routing protocols within the satellite processor and transmitter.
- The other is the local area network protocols at the user group nodes.

Transmission and data routing protocols are especially applicable in the on-board switching model. In the satellite processor, standard frame and other blocked data formats will be used. The on-board processor will read blocked data headers in accordance with the formats established for the applicable protocol, extract the destination and characterization information, and then route the data to the proper transmission media.

In the user group environment, standard ISO layered protocols can be used to achieve the proper network connectivity between users on Mars. Because there is a 40 minute round trip delay incurred in the Mars-to-Earth transmission, special protocol formats may have to be established for this transmission path to take into account this time delay, particularly when transmission requirements call for error-free transmission. Local Area

Network (LAN) protocols reflecting the ISO architecture are candidates for the Mars surface communications systems. All the standard network configurations can be accommodated. This includes the use of packet switching networks and X.25 protocol and the use of ISO 8473 packet network layer protocol as well as the use of upper application layers on virtual paths.

3.4.3 Comparison of the Technologies and Suitability for SEI

The configurations presented in the approaches described above allow communications between users, between users and the Mars habitat, or between a user and Earth. The particular method of communications depends upon the complexity of the user terminal as well as the transmission model selected. Tables 3-1 and 3-2 provide some of the advantages and disadvantages of the various approaches.

3.5 References

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Table 3–1: Bent Pipe Communications System – Advantages and Disadvantages

Access Technique	Advantages	Disadvantages
SCPC	<ul style="list-style-type: none"> • Utilization of proven design technology. • A simple architecture accommodates high data rates. • Suitable for growth; expandable to support full Mars comm. system. • Capable of supporting digital and analog data formats. 	<ul style="list-style-type: none"> • Preassigned operation is inefficient for a small number of user groups. • Central control of frequency pool if demand assignment plan is adopted. • Inefficient use of power amplification since backoff is required to reduce IM noise (up to 6 dB).
FDMA	<ul style="list-style-type: none"> • Preassigned channels can be sized according to traffic conditions. • Technology for transmitting several 4 MHz TV channels is available. 	<ul style="list-style-type: none"> • High power amplifier backoff losses (up to 6 dB). • Frequency planning is complex.
TDMA	<ul style="list-style-type: none"> • Utilizes full capacity of transponder per user group. • Preassigned channels can be sized according to traffic conditions. • Preassigned channels can be sized according to traffic conditions. 	<ul style="list-style-type: none"> • Requires a complex control center on Mars. • Communication coverage limited to footprint of one satellite. • Not applicable for Mars-to-Earth communications. • Requires a very accurate burst time plan control.

Table 3–2: On-Board Switching Communications System – Advantages and Disadvantages

Access Technique	Advantages	Disadvantages
SCPC (On-board switching)	<ul style="list-style-type: none"> • Efficient use of satellite spectrum. • Flexible, can provide growth to support Mars communication system. • Can support AM and FM transmission. 	<ul style="list-style-type: none"> • Requires much more source power than bent pipe communications system. • Complex switch state sequence for connectivity matrix. • Requires transmission and network protocol implementation. • Requires an on-board state switch.
(On-Board processor)	<ul style="list-style-type: none"> • Uplink and downlink modulation can be adjusted to optimize transmission plans. 	<ul style="list-style-type: none"> • Complex on-board switching and processing requires use of advanced solid state technology.
FDMA (on-Board switching)	<ul style="list-style-type: none"> • Supports high density of user support groups. • Supports single hop TV transmission with present technology. 	<ul style="list-style-type: none"> • Requires a call request scheme and central switch control.
TDMA	<ul style="list-style-type: none"> • All advantages of bent pipe; plus • Beam switching flexibility provides efficient use of spectrum while increasing network connectivity. 	<ul style="list-style-type: none"> • All disadvantages of bent pipe; plus • Requires use of complex methods for synchronizing traffic burst and on-board switch state time plans.

- [7] J. Bagwell and C. Mahle, "The Role of Technology in Influencing Future Civil Communications Satellites", *Proc. IEEE*, Vol. 78, No. 7, July 1990.
- [8] D. M. Badi and P. A. Garn, "Conceptual Design of a Synchronous Mars Telecommunications Satellite", NASA Technical Paper 2942, 1989.
- [9] Robert M. Gagliardi, "Satellite Communications", Wadsworth Publications, Belmont, California, 1984.

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Chapter 4

Overview of TNIM Functions to be Automated

This chapter presents the Subtask 1 work concerning “Identification of Functions for Unattended Operations” for a Mars Telecommunications, Navigation, and Information Management (TNIM) system. Mars TNIM will support Mars-based telecommunications and navigation functions for the proposed Space Exploration Initiative (SEI).

This chapter is organized as follows:

- 4.1 Scope and Methodology for Function Identification
- 4.2 Description of Mars TNIM Management and Control Functions
- 4.3 Routing and Transmission Protocols

4.1 Scope and Methodology for Function Identification

This chapter addresses those TNIM network functions required to support communications and navigation in the Mars environment and expands on those network functions common to the entire network.

An expansion of TNIM functions specific to the users and network nodes is assumed outside the scope and resources of this study. Other SEI study groups that are focusing on specific network elements and architectures will need to better define the specific TNIM functional needs of their design.

This study assumes the Mars TNIM architecture is not fixed at the present time. It only assumes the network may be composed of some combination of architectural elements listed in Chapter 3.

Network Management functions covered in this chapter are common to all network nodes and are applicable to most all network architectures. These management or control functions, as they are sometimes referred to, are used to control the TNIM network across

which telecommunications and navigation information will flow.

The TNIM communications system can be modeled as a collection of sites, each of which represents a distinct distributed location where some type of communications equipment resides. These sites are connected as presented in the TNIM architectures described in the previous chapters. The goal of network management or network system control is to maintain user-to-user service under changing traffic conditions, user requirements, and system interruptions. In order to achieve this goal, the best use of the resources available to detect and diagnose faults or service degradation must be applied to maintain service to the user.

The management of current distributed communication networks are performed by technicians located at geographically distributed locations. When a problem develops, each of the technicians attempts to ascertain what he/she believes to be the most appropriate step (or action) to take to resolve the problem. In most cases, the control action taken is determined through coordination among a group of technicians located at different sites. This scenario is very common in managing a telecommunication system where the complex task is performed by a group of people, each of whom has a limited view of the problem.

Given the distributed nature of TNIM, it is fair to assume that the control of the network functions must be distributed. With this assumption and a realistic expectation of a dynamic behavior of the network, a centralized point of control cannot be expected to have complete and accurate knowledge concerning the functioning of the overall network.

There are three major aspects of network management in a distributed environment:

- i. Distributed situation assessment
- ii. Distributed problem diagnosis

iii. Distributed planning

Distributed situation assessment is needed in monitoring system operating status. As stated earlier, in a distributed network, no single node has complete and the most current information on the status of other nodes. Therefore, it is important to provide a mechanism for detecting a problem and identifying the impact of the problem on other nodes of the network, since a local problem may have a significant impact on other nodes of the network. A need for cooperation and communication between the nodes exists in order to assess the overall operating status of the network.

In order to identify the source of a service outage or service degradation, a distributed diagnosis system is required. The source of the faults may come from equipment malfunctions or disturbances from external sources. It is common that a failure occurring in one portion of the network often causes problems elsewhere. Without cooperation among control nodes in a network, no single node is aware of events outside its domain. Correct determination of the source of a problem often requires corroborating evidence from other sources.

Distributed planning should be considered when ways for restoring interrupted services to users must be determined. The major objective is to restore service to the most critical users, which may involve the reallocation of under-utilized resources or preemption of less critical users. Since resource utilization and user priority change over time, and these changes affect the status of the overall network, a sequence of control actions is needed to restore service requires appropriate coordination among the sites that control the network.

Other categories of network management functions include:

- Configuration management,
- Performance management, and
- Accounting management.

Table 4-1 contains a list of network management functions. The functional breakdowns are those defined by the International Standards Organization (ISO).

It is the automation of these network management functions that forms the basis of this study. In Chapter 5 these Network Management functions are examined to determine what technologies are needed to support the automation of unattended Mars TNIM operations.

4.2 Description of Mars TNIM Management and Control Functions

As mentioned in the previous section, Integrated Network Management (INM) functions fall into one of six main categories:

1. Fault Management
2. Configuration Management
3. Accounting Management
4. Performance Management
5. Resource Management
6. Security Management

The following paragraphs describe these functions and list subfunctions where applicable. Possible implementations of these functions are described in Chapter 5. Three common architectures are the centralized, the distributed, and the distributed peer INM as shown in Chapter 5 — Figures 5-2, 5-3, and 5-4.

4.2.1 Fault Management Functions

A comprehensive set of functions for fault handling must be provided. These functions will include detecting, diagnosing, and recovering from network faults. Since much of the TNIM equipment will be difficult to access, fault handling functions must emphasize early prediction and prevention of faults or automated switch over to redundant systems.

Included are functions for the following:

- Prediction of faults through error log monitoring and statistical analysis,
- Prevention through active measures such as equipment shutdown,
- Detection of faults when they occur through monitoring systems,
- Isolation of faults to specific systems through error log and link analysis,
- Correction of faults, and
- Use of contingency procedures when faults occur.

Table 4-1: Mars TNIM Network Functions and Network Interfaces

Users	Network Functions	Network Nodes
Earth networks SEI Control Centers SEI spacecraft, MTV, MEV, Space Station Data processing centers Mars surface science Mars orbiting users	Fault management Configuration management Performance management Resource management Security management Accounting management	Mars relay satellites Mars surface terminal Mars communications hub Deep Space Network TDRSS, ATDRS

4.2.2 Configuration Management Functions

Configuration management functions include defining, changing, monitoring, and controlling network resources and data.

4.2.3 Accounting Management Functions

In order to support the TNIM planning and scheduling functions, the status and availability of network resources must be monitored and maintained. Resource availabilities may vary due to planned outages such as the Mars Telecommunications relay satellites being out of Earth view, or due to unplanned events such as equipment failures.

4.2.4 Performance Management Functions

Performance Management functions include monitoring both the current and long-term performance of the network. Parameters monitored include:

- Effective Link Data Rates
- Link Data Quality
- Time taken for link acquisition
- Link down times

4.2.5 Resource Management Functions

Once high-level priorities and policies are defined and the major events planned, TNIM network resources need to be assigned to support them. This will result in a high-level event schedule and general resource allocation profile. For example, a general resource allocation might allow Mars inhabitants 4 hours per week on a video link to Earth.

Resources managed in the Mars TNIM network include:

- Mars Relay Satellites (MRS) and their resources including antennas, transponders, and RF and Digital equipment.
- Mars Surface Terminals (MST) and their resources.
- Mars Communications Hubs (MCH), if present.
- Deep Space Network (DSN) resources.
- Earth Relay Satellites, if present.

4.2.6 Security Management Functions

Security Management Functions ensure authorized access to the network resources and user information.

4.3 Routing and Transmission Protocols

Routing and transmission protocols in an unattended telecommunication environment should ideally satisfy the following requirements:

- The system should be demand-driven and self-configuring, adjusting automatically to changes in topology caused by equipment failure or degradation, moving targets, or changes in bandwidth requirements.
- The ground systems should require a minimal knowledge of the underlying multiplexing and polling schemes on board the spacecraft. This will make it possible to change the multiplexing/polling algorithm on the spacecraft independent of making the same demands of the ground systems.
- The system should be capable of handling both packet-switched and circuit-switched data.

- The system should be data-driven, requiring little or no advance resource allocation for small extra resource requirements.
- The system should be capable of buffering data to accommodate high-rate data collection, retransmission protocols, link outages, and the differences in transmission rates.
- The system should provide different grades of service according to the criticality of the information being sent. It should provide guaranteed receipt for command and control application, and probability of receipt for other classes of application.

The network management approach should provide the overlying set of services which manage these protocols and ensure that the network accomplishes these functions with minimum user interaction. This objective becomes most important in an unattended environment such as TNIM.

Chapter 5

Assessment of Network Management Technologies

This chapter is organized as follows:

- 5.1 Overview
- 5.2 Network Management Technologies
- 5.3 Fault Tolerance Technologies
- 5.4 References

5.1 Overview

This chapter addresses Subtask 2 of the Statement of Work which requests for an assessment of alternative, innovative, system concepts which might affect technology levels needed for unattended Mars network operations. After reviewing current space-based network approaches (for example DSN, TDRS, NASCOM), it has become evident that few if any innovative system concepts for unattended space network operations are in use or are being developed.

An exception to this is spacecraft fault tolerance technologies where much work has been done. The fault tolerance technologies were thought to be applicable to unattended network operations since these technologies are inherent to the design of an unattended network. An assessment of fault tolerance technologies is given in Section 5.3.

As mentioned above, concepts and technologies for space-based unattended network operations has received little or no attention within NASA. Current space communication networks in use by NASA are very manpower intensive in virtually all functional areas (for example scheduling, acquisition, and problem resolution).

One bright spot however is in the area of commercialized network control. This area includes telephone

and information systems that are very competitive and hence cost conscious. This area has seen much automation of the processes and functions involved, some of which could be applied to a space-based network. Even these networks, however, do not run fully unattended. Here man is still in the loop to handle faults.

It is also possible that the Department of Defense (DoD) has developed autonomous network concepts and technologies, but an extensive review of DoD space programs was not conducted in this study due to time and manpower restrictions.

Obviously there is a strong need for defining and developing the technologies required for an unattended space-based network. Section 5.2 contains the assessments of technologies needed to take man out of the loop in the context of a commercial terrestrial network. This section focuses an Artificial Intelligence (AI) technologies that would replace men in the decision loop with software.

After we learn how to run an unattended network on Earth we can apply these technologies to space networks where new difficulties arise due the long distances and high data rates involved.

5.2 Network Management Technologies

5.2.1 General Discussion

An autonomous telecommunication network management system for the SEI environment must have the following capabilities:

- Manage a combination of interfacility (MCH to the MRS, MCH to Earth), and intrafacility (MCH) net-

works.

- Manage a wide range of network resources from low level devices (e. g. repeaters, modems, etc.), to intermediate systems (e.g., bridges, routers, gateways, etc.) to end systems (terminals, etc.).
- Provide a set of basic management services such as those defined by the ISO, (including fault management, configuration management, accounting management, performance management, resource management, and security management), and to manage heterogeneous communications equipment.

5.2.2 Networking and Communication System Requirements

The three major classes of requirements of an information management system which are levied on a communications network are as follows:

1. Network interconnection,
2. Network bandwidth, and
3. Network management functions.

Appropriate technologies must be selected to manage these three critical areas.

Network Interconnection describes the hardware and software devices required for connecting different network components in a geographically distributed environment. These are generally achieved by interconnecting Local Area Networks (LAN's) and Wide Area Networks (WAN's). Interconnecting heterogeneous networks introduces problems due to the incompatibility of the routing protocols, transmission delays and degradation of the network performance. Network elements such as bridges, routers, and gateways can be introduced to provide the necessary interconnection and translation of addresses and protocols.

Space systems currently under development such as the Space Station and EOS are characterized by diverse protocol sets including high speed avionics busses, token-passing fiber optics busses, high speed parallel interconnections, circuit-switched networks with complex signalling protocols, and broadband networks.

Network Bandwidth describes the ability of a system to store and transmit large volumes of information in a fast and efficient way. In a distributed client-server system, the network is responsible for maintaining connections between the network components. More complex applications are being processed at the workstations in the network instead of the mainframes. These computing nodes perform complex algorithm computations, file transfer and query processing.

Modern computer networks are moving toward distributed server-client architectures where specialized data storage, processing, and input-output functions are transparently distributed across the network. This results in significant requirements for bandwidth, both across links and at the network interfaces and interconnections.

Network Management Functions are the functions provided between the network subsystems such as the following:

- Fault management (detecting, diagnosing, and recovering from network faults) configuration management (defining, changing, monitoring and controlling network resources and data, integration of data, voice, and video information)
- Performance management (tracking tactical and strategic performance of the network including trends analysis)
- Accounting management (recording usage of network resources)
- Security management (ensuring authorized access to the network resources and components)
- Resource management and user directories (supporting directories for managing network assets and user information)

These functions become increasingly complex as the networks become a more significant part of the computing environment and as additional functions are distributed across the network.

5.2.3 Overview of Study Results

Figure 5-1 depicts a suggested roadmap for assessing appropriate technologies for implementing unattended

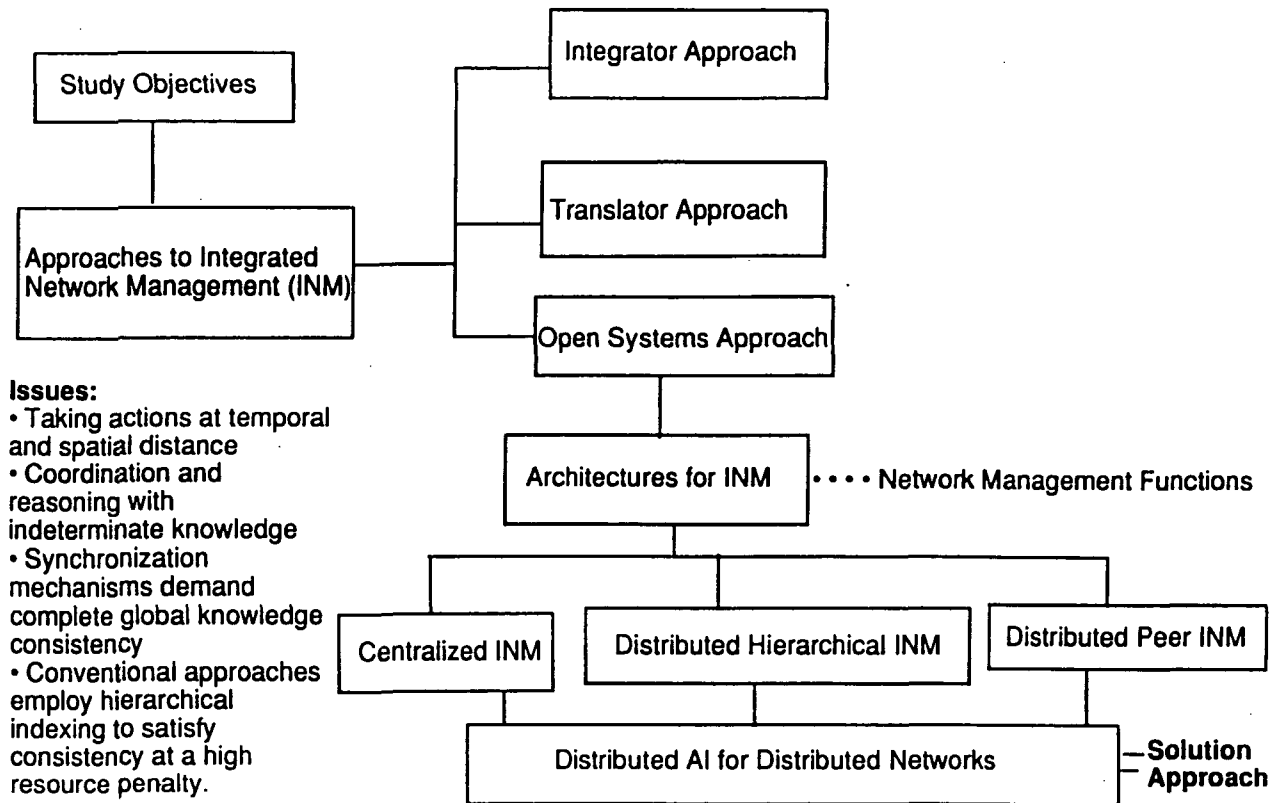


Figure 5-1: Roadmap to Technology Assessment for SEI Unattended Network Management

network management system to meet the objectives of the study. This roadmap identifies the current approaches to Integrated Network Management (INM) and the architectures for INM. Technological issues with conventional approaches to INM implementations in distributed networks are described and protocol approaches for managing network resources are also presented.

The principal result of this study is a recommendation that a distributed/multi-agent problem approach which makes innovative use of conventional software technologies and effective application of emerging software technologies in the field of Artificial Intelligence (AI) is necessary to achieve a truly robust and dynamic network. The conventional network management approaches such as the use of signalling protocols and dynamic routing of communications packets (e. g. ISDN or packet networks) have been found to significantly enhance our capability to provide management functions for TNIM, but these approaches can break down under the following conditions:

- Large time delays
- Poor signal-to-noise ratios

- Limited alternative communications paths
- Lack of human capability to attend to unanticipated problems

These disadvantages can be eliminated through the use of distributed AI which uses embeddable conventional software technologies as agents along with embeddable expert system software systems.

A key benefit of Distributed AI (DAI) in a distributed network is survivability, the capability to substitute or transfer functionality if a node is lost. Other benefits of DAI are presented as well as existing tools and tools being developed in R&D laboratories. One major issue with DAI is distributed coordination. The frameworks for distributed coordination and solution approaches are presented.

A tradeoff analysis of embeddable conventional and AI technologies for DAI is presented in Table 5-1. Conventional discrete event modeling and simulation technology, operations research optimization algorithms, automated data acquisition techniques, and conventional database management system techniques should be investigated for their applicability to performance management, resource management, accounting man-

agement, and data storage and retrieval management of the TNIM system respectively. The benefits and drawbacks of embeddable AI technologies for all the network management functions are also depicted in Table 5-1.

5.2.4 Objectives

Given a heterogeneous mix of computer resources, networked together (via LAN's, satellite links, or other method) to be applied cooperatively toward the solution of a problem, technologies must be developed to address the following key issues:

- Synchronizing the processing times of the distributed processing elements,
- Determining the state of a resource in a distributed system,
- Ensuring the stability (robustness) of a distributed system,
- Verifying the correctness of the execution of the distributed system.

These issues can be addressed and resolved by applying appropriate management technologies to the following three major components of distributed processing:

- i. Computation at the nodes,
- ii. Communication between the nodes,
- iii. Synchronization of the processes.

5.2.5 Approach

The following are the three common approaches employed in the telecommunications industry to integrate heterogeneous communications equipment networked together, (i. e. Integrated Network Management (INM)):

Integrator Approach: separate management tools are integrated by adding a new "supersystem" which has the capabilities to integrate the others.

Translator Approach: one or more of the management systems translates its management information and functions to those of other proprietary systems. The function of the proprietary system is to maintain its own network while allowing other management systems to attach to it.

Open System is a standards-based approach in which all networks' elements and management systems employ a common language and a common set of functions. This approach's main emphasis is the development of an interoperable network management system.

Four major efforts to achieve an architecture for integrated network management are currently being undertaken:

- i. AT&T (Unified Network Management Architecture, UNMA),
- ii. DEC (Enterprise Management Architecture, EMA),
- iii. IBM (Netview), and
- iv. OSI/Network Management (OSI/NM) Forum.

AT&T uses the integrator approach, DEC and IBM employ a translator-like approach, while the OSI/NM Forum (a group of more than 60 international computer and telecommunications equipment vendors and service providers) promotes the use of existing standards and emerging standards to develop a set of specifications which will satisfy an interoperability standard.

5.2.5.1 Possible Architectures for INM Implementations

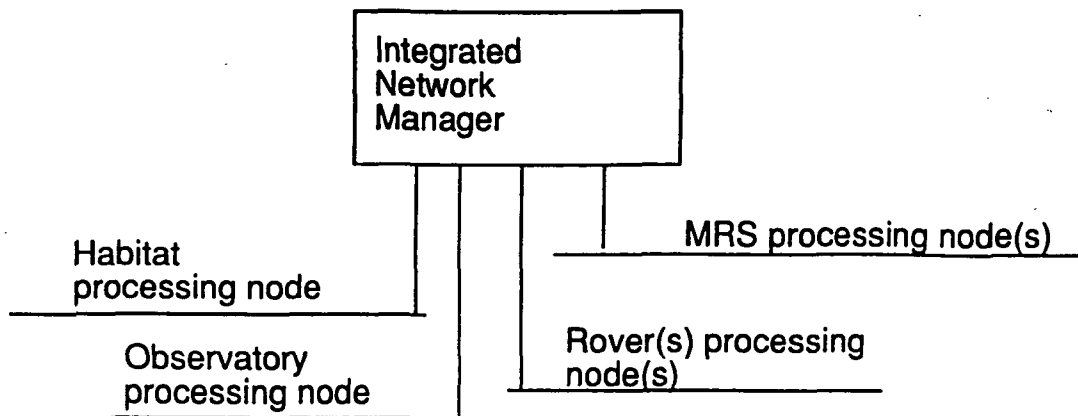
Figures 5-2, 5-3, and 5-4 depict three possible Integrated Network Management (INM) implementations:

- i. Centralized INM with distributed communication nodes,
- ii. Distributed-hierarchical INM, and
- iii. Distributed peer INM.

Each of these implementations must incorporate automated tools for network management functions identified above.

5.2.5.2 Technological Issues with Conventional Approaches to INM Implementations in Distributed Networks

The major problem in implementing a distributed communication network system is how to take action at a temporal and spatial distance. For example, when a



In this configuration, each node is provided with hardware/software to make it operate as an intelligent process with the network manager monitoring the communication between the nodes and synchronization of the processes

Figure 5-2: Centralized Integrated Network Management with Distributed Intelligent Processes

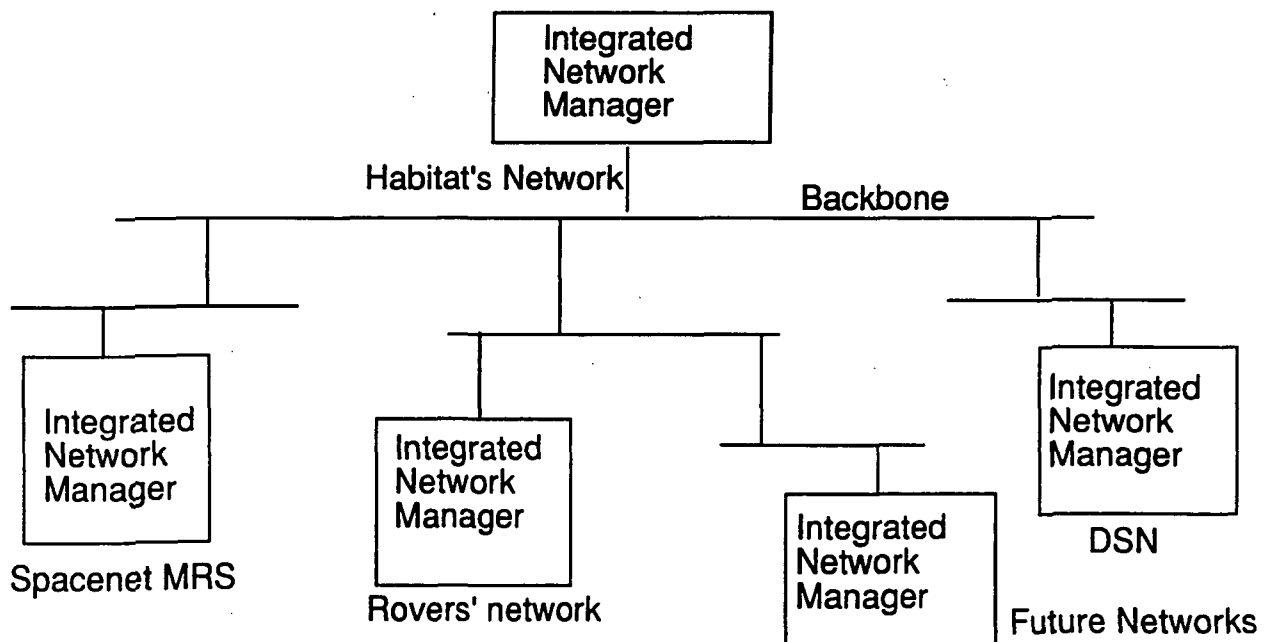


Figure 5-3: Distributed Hierarchical Integrated Network Management

Table 5-1: Technology Tradeoff Analysis – Network Control and System Management Technologies

Management Functions	Technologies	Benefits	Drawbacks
Fault Management	Artificial neural systems	Adaptive	No explanation capability
	Rule-based expert systems	Easy to develop Proven technology	Not adaptive knowledge base updates Maintenance cost of knowledge base
	Hybrid model-based algorithmic systems.	Robust knowledge base	Requires wide knowledge of system Not adaptive
Configuration Management	Hybrid frame/rule-based expert system.	Proven technology Modular design	Not adaptive May require too many rules
	Case-based reasoning and machine learning.	Adaptive	Large storage requirement
	Backward-chaining rule-based systems.	Proven technology	Regular knowledge base updates not acceptable.
	Distributed/concurrent problem solving (AI).	Modular, extensible, fast, adaptable.	Time synchronization and internodal communications issues.
Performance Management	Conventional discrete event simulation.	Proven algorithms	Requires computationally intensive environment.
	Knowledge-based simulation.	Extensibility Modular design	Interface with conventional data base management system (DBMS).
Resource Management	Operations research optimization algorithms. (e.g. linear programming)	Excellent for problems with a small set of constraints.	Expensive solutions for problems with a large set of constraints. May produce infeasible solution.
	Hybrid AI heuristics and conventional resource allocation techniques.	Feasible solution for small and large problems.	Solution is generally suboptimal.
Accounting Management	Automated data acquisition tools.		
Data Storage	Object-orientated DBMS.	Extensible. Intelligent query optimization techniques.	Immaturity of research on persistent knowledge bases..
	Conventional DBMS.	Proven technology.	Inefficient query optimization techniques. Static data formats.

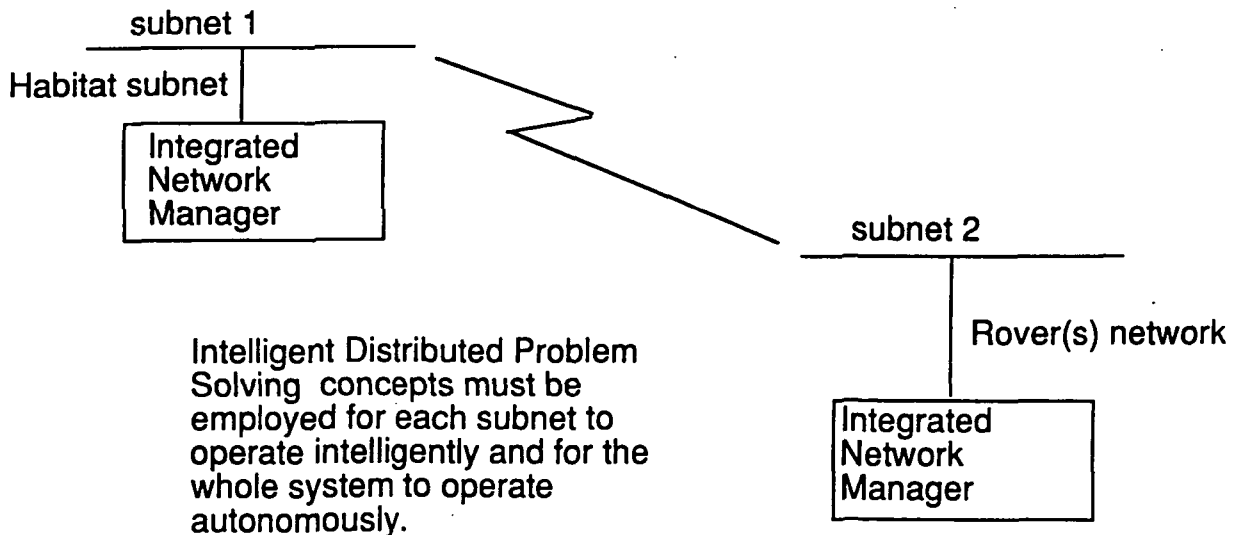


Figure 5-4: Distributed Peer Integrated Network Management

communications link fails, new routing strategies must be coordinated not only at the nodes involved, but also at additional nodes involved in the alternative routing strategy. The problem solver must reason about and coordinate the remote effects of local decisions and reasoning with indeterminate knowledge.

The problems are exacerbated as the scale of the system increases. For example, it may not be possible for a node to immediately determine the status of another node or activate it in time to ensure that network connectivity is maintained. Even current world-wide communications systems (e. g. NASCOM) have serious problems with synchronizing and coordinating communications services. These problems can only be expected to increase as we attempt to expand the communications to include lunar and Mars-based communications nodes.

To minimize these problems hierarchically arranged regional synchronization mechanisms with complete global consistency can be used. However, the strategies to be employed must be carefully designed to cope with time lag and synchronization problems. Hierarchical indexing and synchronization are required for complete consistency, but there is a resource penalty to be paid.

Protocol Approaches for Managing Network Resources. The use of protocols have been widely accepted as an effective means for managing local area and wide area networks in multi-vendor environments. These protocols include:

- Common Management Information Protocol (CMIP),
- Common Management Protocol over TCP/IP (CMOT), and
- Simple Network Management Protocol (SNMP).

The most widely accepted and used protocol is the SNMP.

There are two components to the implementation of SNMP; an Agent and a Network Management Station. The agent is software found on a variety of network elements (bridges, routers, file servers, etc.). The agent collects network statistics for the element on which it resides. The agent forwards the information when requested by a network management station or when an event occurs. Other network management tasks include the status of various network elements, reviewing error situations and dynamically rerouting network traffic

around network nodes which are heavily loaded. Due to its message passing and distributed topology, the SNMP has a design framework which lends itself to implementing a distributed artificial intelligence system.

The difficulty of implementing large scale concurrent networks can be aided by focussing on newer problem solving techniques which do not depend upon complete data consistency or complete knowledge of the environment. Technologies being developed in the AI discipline of Distributed Problem-Solving and Multi-agent Systems otherwise known as Distributed AI provide the tools necessary for managing unattended telecommunication networks.

5.2.5.3 Role of Distributed Artificial Intelligence

Distributed Artificial Intelligence (DAI) is a branch of the AI discipline dealing with the cooperative solution of problems by a distributed and decentralized group of agents. The agents can be simple or complex processing elements.

Distributed artificial intelligence deals with problems that develop when a group of loosely coupled problem solving agents cooperate to solve a problem. In such a problem solving environment, each of the agents has a limited amount of knowledge of the problem and can only gain this knowledge through communication and coordination with other agents. Distributed AI falls into two categories:

- Distributed Problem Solving (DPS)
- Multi-Agent Systems.

Figure 5-5 identifies the two categories and the frameworks for distributed coordination. By combining conventional software problem solving techniques with emerging AI technologies, DAI is able to solve complex problems in a distributed environment. In a telecommunication network, by applying a framework similar to the SNMP, the status of each element or node on the network can be monitored and any faults can be detected with conventional software or hardware technologies. Judicious selection of AI and conventional methodologies can be employed to manage the faults.

A modeling and simulation technique can be employed to monitor the performance of the processing elements within the network. The performance information will help in identifying the constraints within the network. The information about the network constraints can then be used for managing the resources.

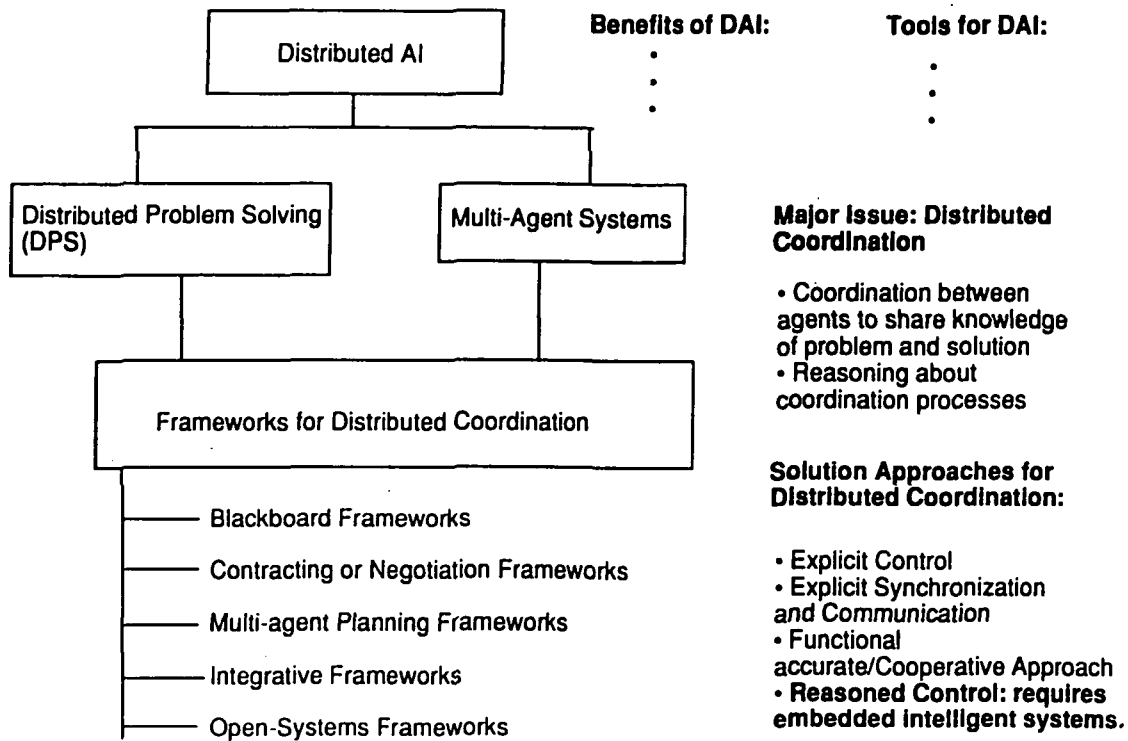


Figure 5-5: Distributed Artificial Intelligence

within the network. A plan for implementing such a system and removing the human element in the loop and thereby achieving a minimally attended network in TNIM is presented in Chapter 6.

Distributed Problem Solving (DPS). This approach deals with how the work of solving a particular problem can be divided among a number of modules that cooperate by dividing and sharing knowledge about the problem and the solution that develops.

Multi-Agent Systems are comprised of intelligent behavior among a collection of autonomous, intelligent agents which can coordinate their knowledge and capabilities to solve problems. These agents may be working towards a single global goal or separate individual interacting goals.

The following are some of the benefits of Distributed Artificial Intelligence:

- Inherent parallelism in the approach speeds up computations and problem solving;
- Reliability and survivability is improved through redundancy;

- Helps to achieve increased modularity and reconfigurability;
- Accommodates open systems (systems with no complete representation and with dynamically changing boundaries);
- Adaptability: concurrent systems are inherently more adaptable than sequential systems;
- Multiple perspectives: different problem solvers can bring several perspectives to bear on one problem.

5.2.5.3.1 Frameworks for Distributed Coordination and Problem Solving. A critical issue with DAI is the problem of coordination between the agents in DPS and multi-agent systems in sharing knowledge on the problem being solved and solution expected; and reasoning about the coordination processes among the agents. Some of the frameworks which have been developed for accomplishing this coordination are as follows:

Blackboard frameworks. A collection of knowledge sources relies upon a global scheduler and a centrally shared knowledge base or blackboard

for communication, consistency and control. This framework can also be used for multiple-interacting blackboard problem solvers.

Contracting or Negotiation Frameworks use bidding, contracting, and information-exchange protocols to allocate work or resolve conflicts.

Multi-agent Planning Frameworks use a single agent or a group of agents to form a plan for solving a multi-agent problem. Dependencies and conflicts among the actions and knowledge of different agents are identified in advance. Each agent is provided with the knowledge about the communication and synchronization needs of other agents. (Problems with reasoning about the effects of concurrent actions.)

Integrative frameworks provide a set of communication and consistency mechanism supporting a number of complementary paradigms for problem solving.

Open system frameworks provide theoretical and practical models of flexible, self-configuring communication and coordination frameworks. These frameworks may include locally reconfigurable communities of agents.

5.2.5.3.2 Issues arising from Distributed Coordination. The issue of how to allocate work to a collection of agents over time to maximize the values of some performance criteria must be resolved. The approaches used vary according to the amount of knowledge each agent has:

Explicit control uses explicit centralized constraints which are minimally adaptive.

Explicit synchronization and communication uses semi-centralized interaction constraints which are adaptive to temporal uncertainties.

Functional accurate/cooperative approach uses semi-centralized opportunistic control with fixed interactions which are adaptive to some temporal uncertainty.

Reasoned control (where agents use knowledge of selves and others to build and revise coordination frameworks). This approach provides predictions and adaptive interactions. It is more adaptive to

semantic, temporal and interactional uncertainty, permits minimal sharing and decentralization.

5.2.5.3.3 Tools for Distributed Artificial Intelligence. Four kinds of tools are available for DAI experimentation and development:

- i. Integrative systems;
- ii. Experimental testbeds;
- iii. Distributed, object-oriented languages; and
- iv. Paradigm-specific shells.

Integrative systems provide the framework to combine a variety of paradigm-specific tools and methods into a useful system. ABE (from TecKnowledge Inc.) is a framework for integrating a number of heterogeneous, independently developed, problem-solving paradigms and software tools. AGORA is an opaque, high level operating system developed to integrate heterogeneous hardware systems under a common operating system.

Experimental Testbeds. Multi-Agent Computing Environment (MACE) is a generic testbed for building DAI systems of varying levels of granularity. MACE allows integration of different problem solving and communication structures by providing the programmers with a collection of tools such as knowledge representation and reasoning tools, pattern matchers and remote demons.

Distributed Object-Oriented Programming

Environments. LISP, C++ and UNIX operating systems.

Paradigm-Specific Shells.

Concurrent Blackboards (e. g. BBOX from TecKnowledge Inc.)

5.2.6 Network Management Functions and Technologies

In general, network management consists of a combination of human, software, and hardware elements. The human elements consist of network administrators who make decisions on network management. The software and hardware elements are the automated network management tools which provide management capabilities for the network. These tools perform the following network management functions:

1. **Fault Management:** detecting, diagnosing, and recovering from network faults.
2. **Configuration Management:** defining, changing, monitoring and controlling network resources and data.
3. **Accounting Management:** recording usage of network resources.
4. **Performance Management:** tracking current and long term performance of the network (trend analysis).
5. **Resource Management and User Directory:** Supporting directories for managing network assets and user information.
6. **Security Management:** Ensuring authorized access to the network resources and components.

These classes of functions correspond to the classes of functions named in the ISO Network Management framework. An architecture for these management functions is described by Figure 5-6.

The Network Interface is the equivalent of a user interface in an attended network management system. It will serve as a monitor for all the management functions. It provides the functions ordinarily performed by a human user.

The Database/Knowledge base stores the data and knowledge about the network. The data is used when conventional software is used for automating some network functions, and the knowledge base is used when expert system tools are used to implement or augment certain network management functions. Distribution and format of this data base are major issues.

The Management Protocol Engine is responsible for providing the means by which the network manager can communicate with the network management functions (agents) in individual network components. It also provides the mechanism for management data acquisition.

Protocol Stacks provide the interface to the networks being managed.

5.2.6.1 Fault Management Technologies

AI technologies such as diagnostic expert systems and artificial neural systems can be used for detecting and diagnosing and corrected network faults. There are currently many excellent off-the-shelf software packages

which provide adequate functionality to support development of robust AI fault management systems.

Diagnostic expert systems rely on the capture of problem information and specific recommendations by human experts. A rule-based expert system uses a combination of a data base which stores rules in IF... THEN format and a set of inference algorithms to make decisions about the characteristics of the problem and appropriate actions.

For simple subsystems rulebased systems with predictably robust performance are easy to develop, but complex systems often require more powerful strategies such as model-based systems. Model-based expert systems use an internally defined model to reason about the system, both to trace causal relationships and explore possible corrections strategies. Hybrid approaches often prove to be the most workable and effective systems.

Artificial neural systems provide excellent means (learning paradigms and models) for detecting errors and classifying errors (diagnosing). Their principal benefits are their ability to provide robust response over widely varying conditions, the ease of programming (training) them to handle new situations, and their capability to provide real-time response once trained.

A combination of the use of artificial neural systems and expert systems is ideal for fault management. Recovery from network faults can be represented as a set of rules which will operate on the results from the Artificial Neural System (ANS) and model-based reasoning systems.

5.2.6.2 Configuration Management Technologies

Configuration management is a prerequisite for effective application of the other elements of network management. The database of all network components (e. g., hardware, software, circuits or lines) must be made available to help in scheduling and tracking of changes to the configuration.

Techniques for configuration management. The artificial intelligence approach can be employed. One approach using a hybrid rule/frame-based methodology can apply a set of rules that specify what a complete or legal solution must include when presented with a set of initial choices from among a set of options, with implications or constraints. It must also apply some conflict resolution rules to arrive at a legal solution. Figure 5-7

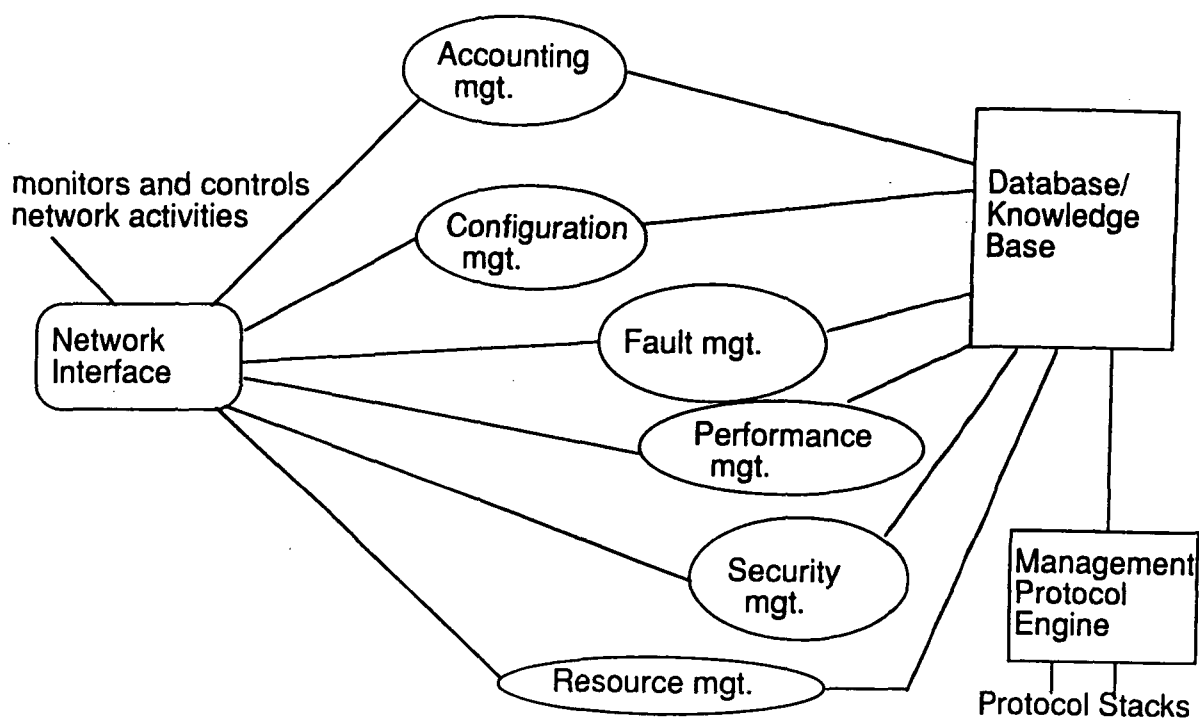
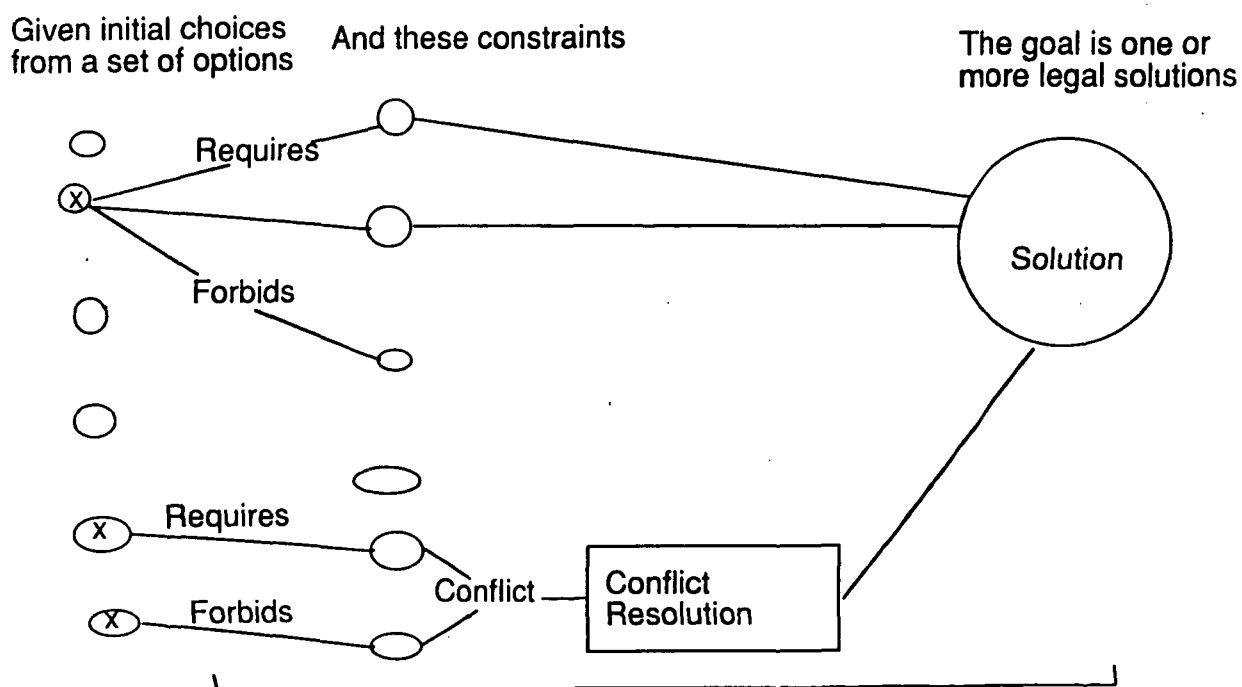


Figure 5–6: Integrated Network Management Architecture



A set of rules that specify what a complete or legal solution must include

Figure 5–7: Configuration Management Process Flow Diagram

presents a process flow diagram for configuration management.

A machine learning technique can be developed and trained with a certain set of examples, and trained to recognize patterns thereby learning how to configure the network when certain patterns appear in the system. Such an adaptive system is better than a rule-based system which will demand that new rules be developed when new situations which has not been represented in the rule base occur. Also, there may be too many rules to write. For an unattended network system, an adaptive system is highly recommended.

Case-Based Reasoning Systems can be applied in configuring a communication network system. If a knowledge of possible cases exists, then by using a library of past cases, the system can reconfigure the network autonomously.

The monitoring part of configuration management can be performed by a backward-chaining rule-based diagnostic expert system which runs repeatedly until a particular recommendation is encountered and then alarms appropriate embedded system, or a forward chaining system that monitors data patterns and informs the controlling function when a particular pattern is encountered.

5.2.6.3 Accounting Management Technologies

Data being generated at different nodes of the network will need to be buffered and retrieved in an efficient manner and in a form understood by a cling agent. It is necessary to investigate efficient data acquisition, storage and retrieval technologies for managing the information. A combination of conventional approached to data management and object oriented data base management technologies will be investigated to handle data generation at each node and data distribution to requesting agents within the network.

5.2.6.4 Performance Management Technologies

This involves measurement and analysis of resource utilization and network response time. Engineering traffic statistics are provided to aid in predictive network performance.

Approaches require discrete event simulation technologies. Knowledge-based simulation techniques and object oriented knowledge representation schemes are employed to aid system modularity and extensibility.

5.2.6.5 Security Management Technologies

Technologies that guarantee the correct coordination of the agents (software) are required for preventing incorrect activation and execution of other agents. These technologies are necessary to ensure a secure and reliable system.

5.2.6.6 Resource Management Technologies

For small and simple tasks, forward chaining, rule-based expert systems or operations research techniques (linear programming) can be used.

Mid-size or large and complex resource management task demand the use of hybrid tools (object oriented and rule-based reasoning).

5.3 Fault Tolerance Technologies

A key issue in providing unattended operations for TNIM is the extent to which the network will be fault tolerant. The TNIM system must provide significant levels of fault tolerance both at the system subsystem, and component levels to achieve its mission. This is driven by a number of considerations:

- Minimal availability of manpower and resources at Mars or in Mars orbit to repair malfunctions.
- Limited capability for remote diagnosis due to the difficulties of Mars-Earth communications (time delay, pointing, bandwidth).
- Critical support requirements during maneuvers such as aerobraking and launch.
- Long mission life including both transit from Earth to Mars and on-site and on-orbit at Mars.
- Need for man-rated reliability during the later phases of SEI.

Most importantly, the long journey time between Earth and Mars and the remoteness of the Mars location dictates that all SEI subsystems be engineered so that they are immune to multiple failures or that mission objectives can be safely carried out in the face of significant loss or degradation of component functions. This requirement is even more critical than previous missions such as Mercury, Apollo, Skylab, or the Shuttle flights since SEI missions will be inherently longer in duration.

TNIM must be engineered so that:

- Components are unlikely to fail during their planned mission life cycle;
- Unanticipated component failures are detected and redundant components are substituted with little or no immediate human input;
- Further subsystem or system-level failure detection and correction mechanisms are available to deal with more serious large-scale failures; and
- As a last resort, degraded modes of operation are available to reduce the risk of loss of life or critical SEI resources while remote diagnosis and correction is performed.

5.3.1 Objectives

The fault tolerance technologies study deals with both system and component level technologies required to achieve the above goals. The objective is to understand the potential failure modes of TNIM equipment, particularly communications satellites and unattended switching equipment, and describe technologies which must be developed to improve potential fault tolerance of TNIM systems. A number of these technologies are also applicable to other SEI systems.

5.3.2 Approach

Several methods of information collection were used in this study. Included were a literature search of existing methods for fault tolerant systems engineering and interviews with Loral satellite operations personnel familiar with communications satellite failure modes.

Within the resource limits of the study we attempted to collect information about existing communications satellite systems and their failure modes, and approaches that have been used both deep space missions and DoD survivable satellite programs where autonomous fault tolerance are critical mission requirements. We also studied a number of NASA, DoD, and commercial communications programs with significant reliability and fault tolerance requirements.

5.3.3 Fault Tolerance Engineering Process

The process of engineering fault tolerant systems is fairly well understood and a substantial body of both

practical engineering and theoretical literature exists including both NASA and DoD standards [7]¹. The most common thread of thought throughout the literature of fault tolerance is that fault tolerance cannot be achieved by ad hoc or piece meal methods [6]. For a system to be fault tolerant it must be designed from start with a clear process for evaluating potential failure modes and engineering in fault tolerance at the systems level.

The steps of a typical fault tolerance engineering process as might be applied to TNIM are as follows:

- a. Identify critical subsystems their elements.
- b. Describe available technology alternatives.
- c. Describe system-level impacts of alternatives (weight, power, thermal, operational complexity, etc.).
- d. Identify and rank for criticality potential failure modes.
- e. Describe potential causes of failure modes.
- f. Identify system architecture alternatives.
- g. Describe fault handling scenarios for each alternative.
- h. Describe and quantify redundancy and fault coverage characteristics for each alternative.
- i. Describe system-level impacts of subsystem failures for each architecture alternative.
- j. Describe system-level reliability (MTBF) and repair (MTTR) distributions for alternatives.
- k. Conduct trades against impacted system parameters.
- l. Investigate potential preventative actions or new system architecture alternatives that minimize impacts.
- m. Select system, subsystem, and element architectures.
- n. Identify contingency provisions to deal with unavoidable risks.
- o. Describe technology development needs to reduce risks.

¹ References are given at the end of the Chapter under "Fault Tolerance Technologies".

TNIM presents a substantial challenge for fault-tolerant engineering at all design levels. Table 5-2 shows some of the issues associated with TNIM system-level communications fault tolerance.

most critical component, the Mars Relay Satellites (MRS) and determine technologies which have the potential to increase reliability and fault tolerance of these systems.

5.3.4 Communication Satellite Failure Modes

The Mars Relay Satellites (MRS's) are the heart of TNIM and are the single most critical portion of the network. Faults which occur on the Earth at DSN ground stations may be detected, locally diagnosed and corrected using techniques identical to those used for existing missions where high levels of man-rated availability are expected. Moreover, it is relatively simple to include additional redundant receivers, transmitters, and antennas to minimize the potential of DSN ground element failure. Reliability of communications equipment on-board SEI spacecraft and on the Mars surface provide a somewhat more difficult problem, but they do not represent critical bottlenecks. Moreover, fault-tolerant technology solutions for the MRS's will also be applicable to these TNIM nodes.

Figure 5-8 shows the typical life of a modern communications satellite and categories of failures. Interviewed operations personnel divided the life of a satellite into three major phases:

Initial Deployment. This phase typically involves the first 60 days of a satellite's life when it is being launched, inserted into geosynchronous orbit, and checked out. The most common failure during this period is launch vehicle failure which accounts for the loss of approximately 5% of all satellites. Design problems are typically detected and corrected during this phase by human intervention. For example, in one of the early Intelsat III launches a bearing seizure problem was solved by rotating the spacecraft so the bearings were cooled.

Routine Operations. This phase represents the core of useful life of the satellite after initial system problems have been fixed, typically for the next 5 to 10 years. For most missions, it is characterized by relatively stable behavior with largely predictable slow degradation of non-mechanical components traveling wave tubes and batteries and run out of

propulsion capabilities. Occasional failures occur, particularly in mechanical components such as data recorders, momentum wheels, actuators, scanning mirrors, and joints. Many problems are fixable by planned subsystem fail-over using redundant systems.

Extended Operations. This phase represents the end of the useful life of the satellite. Some redundant subsystems may no longer be available. Problems which occur at this point are often serious and typically arise in one of four critical system areas, attitude control, communications, power, or data recorders. As in the Routine Operations phase, these failures typically result in systems with substantial mechanical, chemical, or high voltage components. Since backups may not be available, substantial human expertise may be necessary to develop a creative workaround.

In many ways the operation of the MRS's will be similar to that of a typical geosynchronous spacecraft (e. g. TDRS) since communications with Earth-based control systems will be continuous (although limited by link delay and occasional outages due to eclipses). Much of the body of operations and design experience associated with low earth orbit or deep space spacecraft should be sufficient to overcome these problems. The key challenge is to make the subsystems of the MRS sufficiently reliable and provide sufficient fault tolerance so that mission requirements can be fulfilled without interruptions of critical functions.

5.3.5 Critical Technologies

Table 5-3 lists the basic subsystems of a synchronous communications satellite, potential sources of failure, and technologies which have the potential to improve reliability. In the following sections we describe some potential technology developments in the following critical areas:

1. Attitude control
2. Communications
3. Power
4. Data Recorders
5. Fault Detection, Diagnosis, Management, and Repair

Table 5-2: System Level Fault Tolerance Issues

Element or Link	Issues
Mars Relay Satellites (MRS)	Maintenance of critical communications through partial or complete failure of on-board systems for maintaining health and safety. Maintenance of communications under attitude or antenna pointing system degradation or failure. Failover across MRS's.
Mars Communications Hub (MCH)	Failure of critical switching or data buffering systems. Failure of receivers, transmitters, modulators, or demodulators. Potential bottleneck and single-point failure for Earth-Mars communications.
Mars SEI Nodes	Failure of receivers, transmitters, modulators, or demodulators. Failure of local processors and networks. Failure of local data buffers.
In-Transit SEI Vehicles	Maintenance of links during critical maneuvers such as aerobraking. Failure of receivers, transmitters, modulators, or demodulators. Maintenance of high accuracy pointing.
Deep Space Network Ground Stations	Loss of link due to weather outages.
Mars-to-Mars Links	Maintenance of link capability during partial failures (e. g. of an MRS).
Mars-to-Earth Links	Maintenance of link capability during partial failures (e. g. of an MRS). Maintenance of link capability through solar interference.

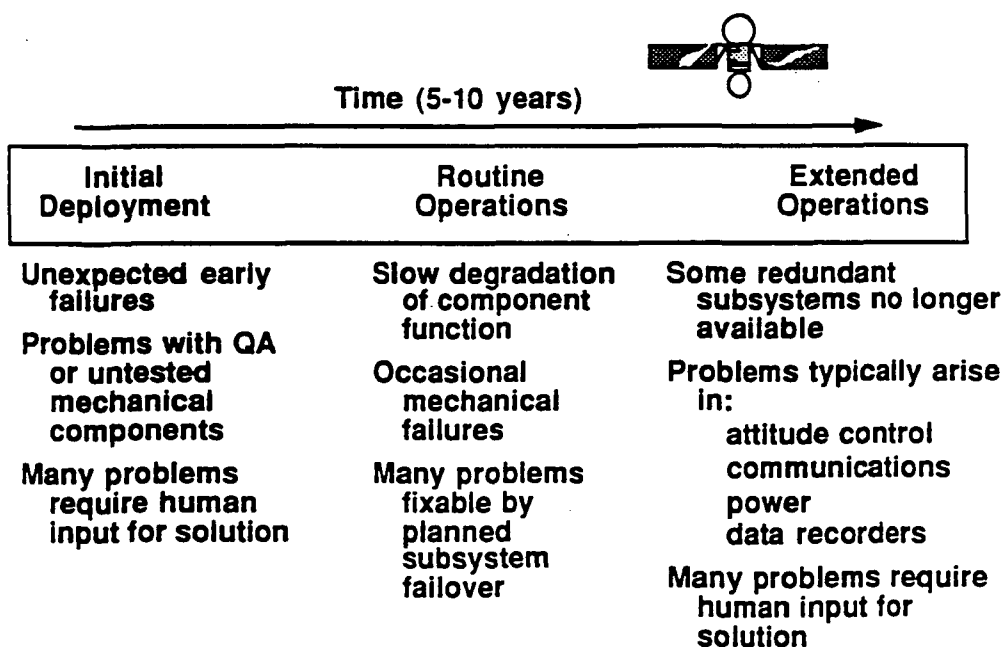


Figure 5-8: Failure Categories of Typical Communications Satellite

Table 5-3: Potential Failures by Subsystem and Technology Development Needed

Subsystem or Component	Potential Failures	Technologies for Development
Attitude Control: Sensors Torquers Angular momentum storage	Horizon sensors mech. failure Momentum wheel failure Loss of earth pointing Pointing noise Aging of electronics	CCD/fiber optics horizon sensors. Low mass star sensors. Low mass, high reliability inertial reference units (e. g. fiber optic gyros, mechanical gyros). Magnetic torquers. Improved gyro configurations to support on-board detection of gyro failures. Solar sails.
Propulsion: Orbit injection Orbit correction Torquer.	Propellant runout Propulsion control loss Valve failure	Ion propulsion technologies. Improved efficiency chemical propulsion systems. Expert system-based detection and correction of valve closure problems.
Electric Power: Power source Storage Control and distribution	Catastrophic short circuits. Battery failure. Relay failure. Long term radiation damage. Aging of electronics. Mechanical failure of solar array pointing mechanisms.	Low mass, nuclear power sources. High efficiency solar cells. Low mass, high reliability batteries. Recyclable fuel cells. Intelligent power control systems. Non-mechanical relays and power switching systems.
Thermal Control: Coatings Insulation Active control	Heater malfunctions. Aging of coatings and blankets.	On-board thermal modeling and protection. Expert system-based detection and correction.
Structure: Main structure Deployment mechanisms	Deployment mechanics failure.	Composite materials. Zero-gravity mechanical engineering.
Telemetry, Command, and Data Processing: On-board computers and network interfaces Encoders and muxes Decoders and demuxes	Software errors and failures. Single bit transient errors. Multiple hard errors due to radiation bursts.	Software-based fault tolerance. Improved software validation techniques. Redundant processor networks. Wafer-scale integration. Radiation-hardened integrated circuits.
Communications: Antennas Switching Transponders Receivers Transmitters	Antenna rotary joint failure. Traveling wave tube failure. Aging of electronics.	Coupling and bearing technology. Solid state Ka-band power amplifiers. Optical communications. MMIC technology.
Data recording and playback	Tape recorder failure.	Solid state recorders. Optical recorders.
Launch: Earth to LEO transport LEO to Mars transport	Launch system failure.	High reliability launch vehicles. On-orbit gas and coil guns.
Operations	Operator error.	Automated validation of command sequences both on-ground and on-board.

5.3.5.1 Attitude Control

Existing three-axis stabilized spacecraft rarely need commanding or correction of the attitude control functions. In a sense this is the most automated set of functions in a modern satellite. For deep space spacecraft significant fault tolerance is an essential requirement in the attitude control system. For example, the Attitude and Articulation Control System of Galileo has significant fault tolerant, adaptive algorithms, detects scan platform pointing disturbances (e. g. spacecraft motion, actuator friction, and structural flexibility) and autonomously compensates.

Principal failure modes involve mechanical elements of the attitude control system, particularly momentum wheel failure, gyro failure or failure of scanning mirrors used in earth/sun/star sensors. Potential improvements in gyro configurations [5] may lead to enhanced ability to support on-board detection or correction of failures. Use of fiber optics or micromechanical gyros may improve the reliability of inertial reference units and allow additional redundancy at no additional weight [1]. For example, Boeing Aerospace and Electronics has developed a 0.5 kg breadboard containing fiber optics gyros and accelerometers under an Air Force contract. CCD or fiber optics-based sensors may remove the danger of failure of mirror mechanics in Mars/sun/star sensors.

A potential additional benefit of these technologies may significantly reduced spacecraft mass, potentially allowing the incorporation of additional redundancy (e. g. the attitude control system is nearly 10% of the Intelsat V dry mass). Moreover, a ripple through effect may result in decreased power, thermal, and fuel requirements, allowing further reliability to be incorporated in the spacecraft systems.

5.3.5.2 Communications

Traveling Wave Tubes (TWT's) used in spacecraft communications systems are now typically delivering over 100,000 hours Mean Time Before Failure (MTBF) in space applications. They are subject to both long-term degradation and occasional catastrophic failure due to their high voltage requirements. The power required for Ka-band TWT's is substantially beyond the capabilities of current reliable TWT technology and as such is a key issue in MRS fault tolerance. Moreover, operation of TWT's at high powers may require additional cooling systems, further affecting system reliability through introduction of additional spacecraft components. There

is some potential for the substitution of solid state power amplifiers as a potential measure to increase communications reliability, but the high operating powers may also have some effect on amplifier life and introduce the need for additional cooling capabilities.

Monolithic Microwave Integrated Circuits (MMIC) technology has the potential to substantially reduce the size, power requirements, parts count, and wiring complexity of on-board communications electronics. Each of these factors affects reliability. Moreover, the development of electronically steerable antenna arrays facilitated by MMIC technology may reduce the MRS requirements for failure-prone mechanical antenna actuators, a significant issue given the size and complexity of potential antenna array designs.

Optical link technologies have been advocated a way to increase throughput and reduce weight of MRS's. However, the microradian pointing accuracies required for optical links introduce a potential new problem of reliability of fine pointing mechanisms. This may force the introduction of backup radio frequency links with additional penalties in size and complexity and potential additional problems in reliability. Additional reliability problems may also result from high voltage circuits required for gas or solid lasers and the relatively short operational life of laser diodes operating at high power levels.

5.3.5.3 Power

Power is typically considered to be the most critical of spacecraft systems since all other functions are dependent. Critical problems associated with power are occasional catastrophic bus failure, long-term degradation of battery function, or loss of pointing capabilities for solar arrays. Significant improvements in reliability may be feasible if we can develop low-weight nuclear power sources (e. g. radio-thermal generators) to reduce battery and solar array requirements without the substantial weight penalties associated with the sources used in current deep space missions. Catastrophic bus failures may be controlled to some degree by providing redundant power buses and control, but there is substantial potential for enhanced on-board power monitoring and control capabilities to reduce potential damage from electrical component failures.

5.3.5.4 Data Recorders

On-board data recorders are notoriously unreliable and difficult to manage. Any buffering at the anticipated data rates that is done on MRS's will provide significant operational and reliability problems. Potential technology developments that may improve reliability of on-board data recording systems include the development of massive space-qualified semiconductor memories such as those being developed by Fairchild or space-qualified optical disks such as those being developed by GE under contract to Langley Research Center.

Since optical disks require some mechanical parts and precise positioning mechanisms they may be an inherently less fault tolerant technology than massive semiconductor memories, but their substantially higher data densities (by several orders of magnitude) may be necessary to fill TNIM requirements for buffering multi-megabit per second data streams.

5.3.5.5 Fault Detection, Diagnosis, Management, and Repair

Given the 40 minute potential delay in Earth-Mars communication, an MRS should provide internal mechanisms to detect and correct internal faults. Some effort has been performed in this area through efforts such as satellite autonomy research funded by the Air Force Rome Air Development Center or by JPL. Much of the work in general large-scale fault detection and correction has been superseded by relatively tightly focused efforts in improving autonomy of specific subsystems. Probably the most successful instance of this sort of capability are the on-board mission sequencing and fault detection, isolation, and correction capabilities in deep space efforts like the Galileo spacecraft.

JPL has defined a number of levels of sophistication associated with control of fault recovery for spacecraft systems:

Level 0: Passive control with no active functions (e. g. gravity gradient).

Level 1: Minimum active control, single string, no redundant functions.

Level 2: Redundancy and cross strapping, ground commanded switching.

Level 3: Internal sensing of prespecified mission-critical faults with self preserving switching. In-

cludes use of dead-man timer, automatic safe-hold entry.

Level 4: Self-checking of hardware commands to avoid internal faults. Ground interaction required for fault recovery.

Level 5: Autonomously fault-tolerant to faults defined a priori. Senses faults, performs management or switching (e. g. switch to redundant IR detectors in an Earth sensor). Has contingency programs on-board. Specified operation not degraded by single faults.

Most subsystems for current communications satellites tend to be at Levels 2 or 3. Ideally, the most critical subsystem functions for MRS's should be at Level 5. In principal there are no major technical constraints associated with developing this level of autonomy (assuming some minor improvements in space qualified computers and spacecraft control software).

A key issue is coverage, i. e. the extent to which faults can be detected, diagnosed, and corrected before serious damage is done. Coverage can be improved by a variety of strategies:

Passive techniques: making sure that critical parameters (e. g. temperatures) change slowly, so that there is sufficient time for earth-based or on-board systems to detect and correct faults.

Hierarchical fault detection and management schemes: providing a hierarchy of fault detection and diagnostic schemes (e. g. expert system-based) to fix faults.

Heartbeat signals: Regularly required "I am well" messages from subsystems monitored by a centralized or distributed health and safety subsystem (e. g. as used in Voyager).

Voting techniques: Multiple control systems governed by voting logic (e. g. such as used in the Apollo lander or Shuttle avionics or Stratus computers).

Model-based techniques: Maintenance of computer models and comparator logic to test whether the real subsystem is behaving in a manner similar to the model.

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Chapter 6

Technology Development Plan

In this chapter, we present a plan for developing the necessary technologies for unattended telecommunications network management. Such a program must be multifaceted, emphasizing development of more robust underlying technologies for satellite telecommunications, including hardware, communications protocols, and control software. Some areas such as the development of more fault tolerant communications satellite technology have a significant overlap with other areas of SEI, since a comprehensive approach to fault tolerance is critical for nearly every SEI function.

We recommend the development of a testbed for using new technologies and innovative use of existing technologies to determine optimum performance approaches for implementing Mars unattended communications networks and the feasibility of applying these technologies to the Mars mission requirements. We divide the development of this testbed into the following stages:

Initial simulation and modeling: a

comprehensive program of simulation and modeling designed to provide an early understanding of the performance characteristics of proposed TNIM network management strategies and the impact of these strategies on SEI operations.

Earth-based networking: tests of TNIM network management concepts using existing Earth-based networks, existing communications satellites, and near-Earth resources such as ACTS.

Lunar operations: tests of TNIM network management concepts during the lunar exploration phase of SEI.

Preliminary Mars-based operations: early tests of TNIM network management concepts using early Mars-based resources.

This chapter is organized as follows:

- 6.1 Testbed for Managing Network Resources
- 6.2 Basis of TNIM Network Management Testbed Approach
- 6.3 Objectives of the Testbed
- 6.4 Distributed Artificial Intelligence
- 6.5 Schedule and Resources

6.1 Testbed for Managing Network Resources

Earth-Mars communications delays, a major design driver for TNIM network management, are significantly less for near-Earth and Earth-Moon links. As a result we may be able to initially learn more from simulation and modeling about the effectiveness of TNIM network management strategies than from early space-based tests. With an appropriately constructed modeling environment, it would be easy to introduce factors which simulate time delays, geometric blockages based on orbit behavior, and deep space noise sources, and iterate to an optimized network management architecture at a relatively low cost. Additional operational experience in a space environment would then serve to further validate the models and architecture.

For this reason we have focused on proposing a simulation and modeling testbed which can provide an early understanding of TNIM network management issues and provide a basis for further planning of space experiments to validate these concepts. The principal objective of the testbed would be to determine what approaches and what distribution of management can best support unattended network management in the context of TNIM.

6.2 Basis of TNIM Network Management Testbed Approach

At the present, local area and wide area networks consist of multi-vendor environments. The use of protocols have been widely accepted as an effective means for managing these networks. These protocols include:

- Common Management Information Protocol (CMIP)
- Common Management Protocol over TCP/IP (CMOT)
- Simple Network Management Protocol (SNMP)

Although CMIP is regarded as the future of network management, it is still being developed and no off-the-shelf tools or networks have CMIP capabilities. The most widely accepted and used protocol is the SNMP.

The SNMP has a design framework which lends itself to implementing a distributed network management system based on the concepts described in Chapter 5 of this report. There are two components to the implementation of SNMP:

- Agent
- Network Management Station

The agent is software found on a variety of network elements (bridges, routers, file servers, etc.). The agent collects network statistics for the element on which it resides. The agent forwards the information when requested by a network management station or when an event occurs. Other network management tasks include the status of various network elements, reviewing error situations and dynamically rerouting network traffic around network nodes which are heavily loaded.

We propose that NASA fund an effort to create an integrated testbed which would initially utilize SNMP concepts to model agent and network components of a series of TNIM architectures. Initial modeling would take place within a single workstation with software processes designed to simulate TNIM nodes and links. Such a simulation would be highly parameterized and include specific software elements to model communications delays and outages based on orbit geometry and known models of deep space communications interference. Specific faults and communications loads could be introduced into the model and the performance of

the model under various conditions could be monitored and analyzed.

Initial strategy would be to purchase an off-the-shelf network management package based on SNMP and insert software elements which would support detailed modeling of TNIM nodes, links, and management functions. Over a period of several years the approach would be expanded to include management of selected TNIM network functions emulated by Loral or NASA computers and links in a geographically dispersed network using either domestic satellite links or NASA-provided facilities such as ACTS.

6.3 Objectives of the Testbed

The proposed test bed would have the following objectives:

- Identify candidate TNIM distributed network management architectures and provide preliminary estimates of network performance under anticipated communications scenarios.
- Test the performance of routing protocols and their ability to provide connectivity and dynamic response to network loading.
- Identify and test strategies for routing network traffic under both routine link interruptions and equipment failure.
- Support an iterative process of discovery of new TNIM network management requirements through experiment, observation, and analysis.

6.4 Distributed Artificial Intelligence

As described in the previous sections, Distributed Artificial Intelligence (DAI) deals with the cooperative solution of problems by a decentralized group of agents (i. e., software programs on distributed nodes). The group of agents is decentralized so that both control and data are often logically or physically distributed. Since there are several architectures and paradigms for implementing cooperative problem solving in a distributed environment such as a distributed communication network, the proposed testbed would serve to support the investigation of the effectiveness of tools for DAI in unattended communications network applications.

Specifically, we would evaluate the following:

Table 6-1: Schedule for Unattended Network Management Testbed

Months after Start	Development Step
1-3	Develop testbed requirements and procure equipment and software.
4-7	Develop alternative TNIM architectures and configure SNMP and simulation software.
8	Develop scenarios for testing of TNIM architectures.
9-12	Conduct testing and prepare report on results.
13-16	Develop approaches for distributed intelligent network management.
17-20	Develop and embed distributed agents in SNMP software.
21-24	Test system and report results.

ABE is a framework for integrating a number of heterogeneous, independently developed, problem-solving paradigms and software tools;

AGORA is a layered environment which supports the design and development of large evolutionary problem solving systems;

MACE (Multi-Agent Computing Environment) is a testbed for building experimental DAI systems at different levels of abstraction. Just as in SNMP, MACE computational units are called agents, with parallel executions. MACE has the added capability of communicating via messages which makes the system more modular.

AF (Activation Framework) supports the implementation of real-time artificial intelligence programs on multiple interconnected computers. It is based on a model of a community of experts communicating by passing messages among one another.

SNMP software	\$15,000
Modeling and simulation software	\$18,000
X-windows, Unix and C software	\$3,000
Sun SPARC workstation	\$13,000
DAI tools	\$10,000
2 full time equivalents, 2 years	\$416,000
6 round trips to Cleveland, Ohio	\$6,000
Estimated total cost	<u>\$481,000</u>

The products of the proposed testbed efforts would be as follows:

- Series of reports describing model design, network management architecture alternatives, and experiment results.
- Multiple models of TNIM network management architectures including documentation and analyses.
- Quarterly reports and design review presentation materials.

Results from this testbed would serve as the basis of further development of space-based tests of TNIM network management concepts.

6.5 Schedule and Resources

In this section we describe a limited plan for building an initial testbed for the development of TNIM unattended network management concepts. Preliminary development could be performed according to the two-year schedule given in Table 6-1 and illustrated in Figure 6-1.

The cost of developing the proposed testbed would be approximately the following in 1991 dollars:

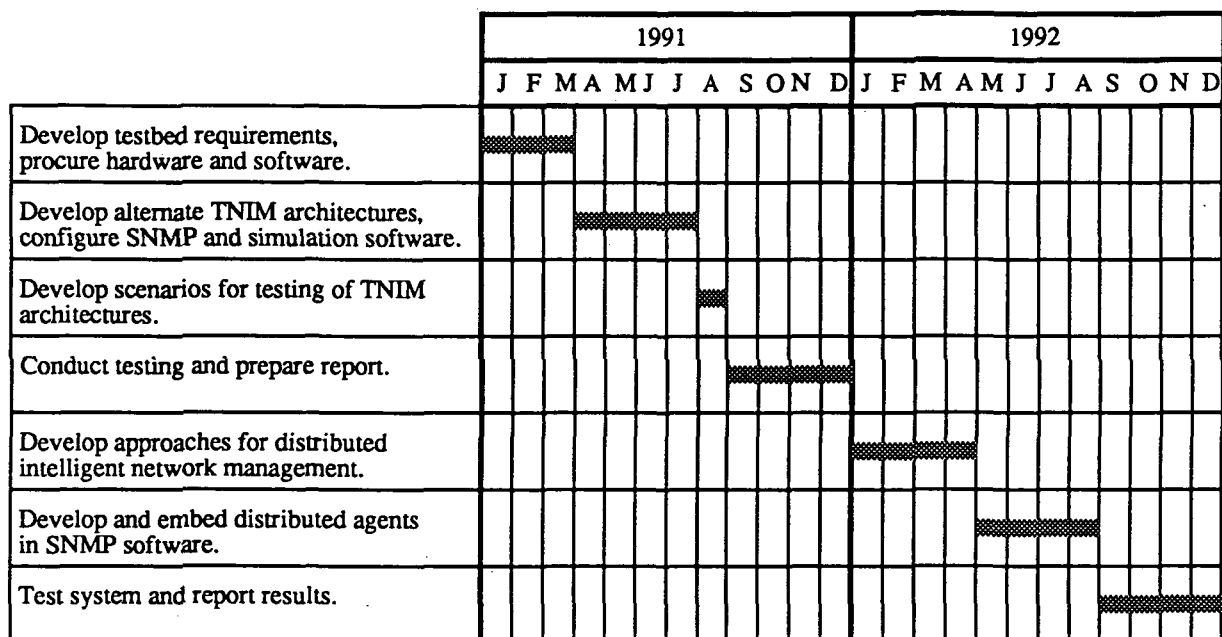


Figure 6-1: Two-Year Schedule for Testbed Development for Mars TNIM Unattended Network

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16. Abstract This report summarizes the results of an unattended network operations technology assessment study for the Space Exploration Initiative (SEI). The scope of the work included: (1) identified possible enhancements to the proposed Mars communications network; (2) identified network operations functions for virtually unattended network operations on Mars; (3) performed a technology assessment of possible supporting technologies based on current and future approaches to network operations; (4) developed a plan for the testing and development of these technologies. The most important results obtained are as follows: (1) addition of a third Mars Relay Satellite (MRS) and MRS cross link capabilities will greatly enhance the network's fault tolerance capabilities through improved connectivity; (2) network functions can be divided into the six basic ISO network functional groups; (3) distributed artificial intelligence technologies will may augment more traditional network management technologies to form the technological infrastructure of a virtually unattended network (4) a significant effort is required to bring the current network technology levels for manned space communications up to the level needed for an automated fault tolerant Mars communications network.					
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